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Middle and Late Pleistocene environmental history of the Marsworth area, south-central England

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ABSTRACT

To elucidate the Middle and Late Pleistocene environmental history of south-central England, we report the stratigraphy, sedimentology, palaeoecology and geochronology of some deposits near the foot of the Chiltern Hills scarp at Marsworth, Buckinghamshire. The Marsworth site is important because its sedimentary sequences contain a rich record of warm stages and cold stages, and it lies close to the Anglian glacial limit. Critical to its history are the origin and age of a brown pebbly silty clay (diamicton) previously interpreted as weathered till.

The deposits described infill a river channel incised into chalk bedrock. They comprise clayey, silty and gravelly sediments, many containing locally derived chalk and some with molluscan, ostracod and vertebrate remains. Most of the deposits are readily attributed to periglacial and fluvial processes, and some are dated by optically stimulated luminescence to Marine Isotope Stage (MIS) 6. Although our sedimentological data do not discriminate between a glacial or periglacial interpretation of the diamicton, amino-acid dating of three molluscan taxa from beneath it indicates that it is younger than MIS 9 and older than MIS 5e. This makes a glacial interpretation unlikely, and we interpret the diamicton as a periglacial slope deposit.

The Pleistocene history reconstructed for Marsworth identifies four key elements: (1) Anglian glaciation during MIS 12 closely approached Marsworth, introducing far-travelled pebbles such as *Rhaxella* chert and possibly some fine sand minerals into the area. (2) Interglacial environments inferred from fluvial sediments during MIS 7 varied from fully interglacial conditions during sub-stages 7e and 7c, cool temperate conditions during sub-stage 7b or 7a, temperate conditions similar to those today in central England towards the end of the interglacial, and cool temperate conditions during sub-stage 7a. (3) Periglacial activity during MIS 6 involved thermal contraction cracking, permafrost development, fracturing of chalk bedrock, fluvial activity, slopewash, mass movement and deposition of loess and coversand. (4) Fully interglacial conditions during sub-stage 5e led to renewed fluvial activity, soil formation and acidic weathering.

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1. Introduction

The most complete records of Quaternary time are found in the deep marine sediment sequences (Lisiecki and Raymo, 2005) or long ice core records (EPICA, 2004; Jouzel et al., 2007). These sequences are long, fairly continuous and relatively free of hiatuses. In the terrestrial realm the situation is more complicated (Bowen, 1999). Terrestrial deposits rich in environmental and stratigraphic indicators frequently represent short-lived periods of sediment accumulation bounded by major unconformities (Candy et al., 2010). Constructing a robust terrestrial stratigraphy for them is complicated and challenging. Essential to such stratigraphy are single sites that record episodes of deposition relating to discrete and distinct climatic phases of varying age (Rose, 2009). It is only through such sites that biostratigraphically distinct assemblages can be placed into a relative order and the temperate stage deposits can be related with the lithostratigraphically important deposits of cold stages (Rose, 2009).

The site of Marsworth, Buckinghamshire, is crucial to understanding the late Middle and Late Pleistocene stratigraphy of lowland Britain because its sedimentary sequences contain a rich record of warm stages and cold stages, and it lies close to the Anglian glacial limit. It has been an important site in establishing the credibility of an interglacial between the Hoxnian and the Ipswichian. The deposits at Marsworth contain a particularly well-preserved sedimentary sequence that spans at least two temperate and one intervening periglacial episode during the late Middle and Late Pleistocene (Green et al., 1984). The infills of two river channels have been assigned to MIS 7 and 5e, and the intervening sheet of periglacial slope deposits to MIS 6 (Murton et al., 2001). High-precision uranium-series dating of tufa fragments from the older river channel suggests that tufa formed during both sub-stages 7e and 7c, and that the main part of the channel fill accumulated during either sub-stages 7b or 7a (Candy and Schreve, 2007). Nearby a diamicton tentatively interpreted as weathered till (Whiteman, 1998; cf. Avery, 1964) overlies fossiliferous deposits of uncertain age and palaeoenvironmental significance. Because the diamicton is located c. 4–5 km to the south of the Anglian Ice Sheet limit (Fig. 1; Horton et al., 1995), the hypothesis needs to be tested that Anglian ice extended further south across the Vale of Aylesbury to Marsworth or that any later ice sheet reached this area, impinging on the adjacent scarp slope of the Chiltern Hills.

Here we report the stratigraphy, sedimentology, faunal remains and geochronology of the fossiliferous deposits within a third small stream channel that underlies the enigmatic diamicton. We provide new evidence for unstable environmental conditions during MIS 7 inferred from molluscan assemblages, and evaluate the origin of the overlying diamicton and associated deformation structures. We establish the age of the third channel sequence, spanning MIS 7 to 6, with amino-acid analyses of three molluscan taxa and optical dating of quartz sand grains. This allows us to reconstruct the Middle and Late Pleistocene environmental history of the Marsworth area, making the site one of the richest known palaeoenvironmental archives of this period in south-central England. Micromorphological data were collected during the present study by C.A. Whiteman and may be discussed elsewhere (C.A. Whiteman, pers. comm., 2014).

2. The study area

2.1. Physiography and bedrock geology

The physiographic units relevant to the present study are the Chiltern Hills cuesta, the Icknield Belt platform, and the Vale of Aylesbury (Fig. 1).

The Chiltern Hills cuesta is underlain by the White Chalk Subgroup (Mortimore et al., 2001) that gently dips to the southeast. The upper part of this subgroup, the Lewes Nodular Chalk and overlying formations, usually contains more than 97% calcium carbonate and abundant flints. The Chiltern scarp slope is located c. 1 km southeast of Marsworth, rises from c. 150 m to c. 210–245 m Ordnance Datum (O.D.), and is dissected by numerous, short dry valleys (Fig. 2a). Further southeast, the dip slope is dissected by a network of long dry valleys and is widely mantled by Clay-with-flints and Plateau Drift (Fig. 1; Loveday, 1962; Avery, 1964, pp. 2–4).

The Icknield Belt platform, on which rest the Pleistocene deposits described in this paper, slopes gently towards the northwest from the scarp foot (Fig. 1). The platform is c. 3 km wide near Marsworth and lies mostly at an elevation of between c. 120 and 150 m above O.D. Its northwest margin is delineated by a low scarp that rises from c. 100 m to 130 m O.D., on which is located the village of Marsworth (National Grid Reference SP 922144). The platform is underlain by the Grey Chalk Subgroup and the lower part of the White Chalk Subgroup (Mortimore et al., 2001). The former is grey, marly and lacks flints. Beneath the Marsworth Pleistocene deposits, the Grey Chalk Subgroup consists mostly of Zig Zag Formation Chalk, whose basal unit, the Totternhoe Stone Member, subcrops near section C_2. The platform near Marsworth is at the mouth of the Tring Gap (Gregory, 1914; Sherlock, 1924), one of six major valleys (or 'gaps') that cross the Chiltern cuesta (Fig. 1). Five of the gaps are dry ('wind gaps'), whereas the sixth, easternmost one is occupied by the River Lea, near Luton and Harpenden. The gaps have thresholds at elevations of between 155 m and 120 m, and their floors decline in elevation southeast towards the Vale of St Albans and the London Basin Lowlands (Jones, 1981, pp. 34–35).

The Vale of Aylesbury is a lowland drained mostly by the headwaters of the River Thame, a tributary of the River Thames. The southeastern margin of the vale, c. 1–1.5 km north and west of the Marsworth Pleistocene site, is marked by the scarp of the Grey Chalk Subgroup platform. To the west and north of the village of Marsworth, the Vale is at c. 80–100 m O.D. and underlain by the Albian Gault Formation (Upper Cretaceous), which is replaced by Upper Jurassic Kimmeridge Clay Formation and Portland Group further to the northwest, near Aylesbury (Fig. 1).

2.2. Pleistocene geology

Superficial deposits identified by the British Geological Survey (BGS) near Marsworth are shown in Fig. 1. Gravels occur both within and to the northwest of the Tring Gap, mapped respectively as 'Valley Gravel' and 'Gravel opposite Chalk Gaps' (Sherlock, 1922, 1924). The valley gravel comprises abraded flints and, in places, Palaeogene flint pebbles, and generally lacks far-travelled material such as quartzose pebbles (Sherlock, 1924). In the Bulbourne valley it passes northwest through the Tring Gap, e.g. near Park Hill Farm (Fig. 2a; Barrow and Green, 1921), fanning out, rising in elevation and dividing into eastern and western lobes in front of the Chiltern scarp (Fig. 1). The gravel has been attributed to fluvial and glaciofluvial deposition during retreat of a glacier banked against the Chilterns, with streams flowing down both the scarp and the ice margin (Sherlock, 1922, 1924). Similar valley gravels occur in other gaps in the Chilterns, at Dagnall, Wendover and Princes Risborough (Fig. 1), including the Princes Risborough Sand and Gravel, which Horton et al. (1995) attributed to deposition by rivers that flowed south-eastwards through the Chalk cuesta, as the present River Thames does through the Goring Gap. According to Sumbler (1995), these former 'consequent' rivers flowed down the Chalk dipslope towards the Thames; their valleys, now truncated by the Chiltern scarp, are higher than, and therefore

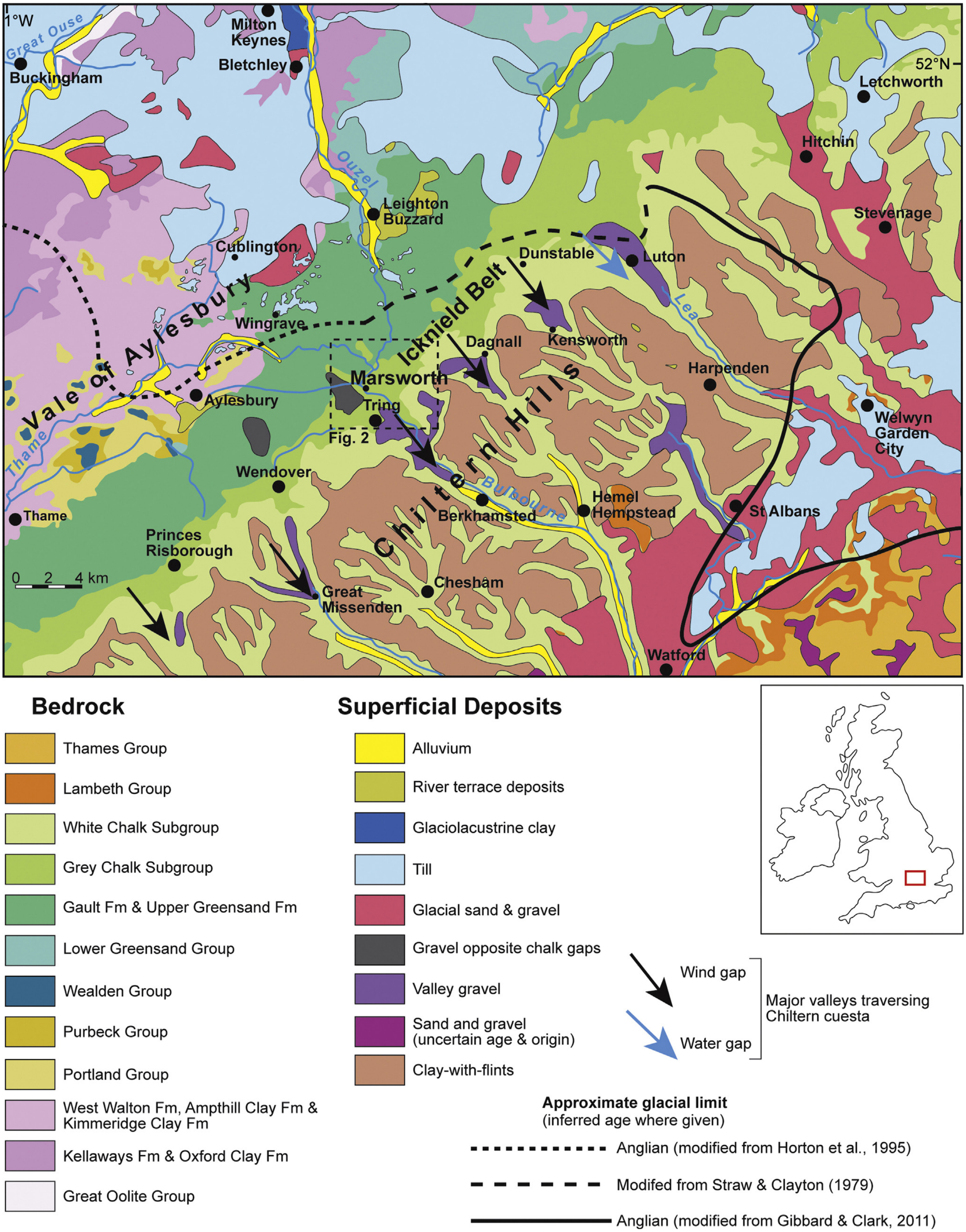

Fig. 1. Geological map of the Chilterns Hills and lowlands to the north and south. Lithostratigraphic units are based primarily on the Geology of Britain viewer of the British Geological Survey (http://mapapps.bgs.ac.uk/geologyofbritain/home.html?mode=boreholes). General distribution of till sheets is shown in the northern and eastern part of the map, and detailed distribution of mapped small patches of till is shown near the inferred glacial limit in the Vale of Aylesbury. Distribution of high-level chalk and flint-rich gravels (termed 'valley gravel' in the legend) in the Princes Risborough gap according to Horton et al. (1995, Fig. 24). Red rectangle in outline map shows location of Fig. 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

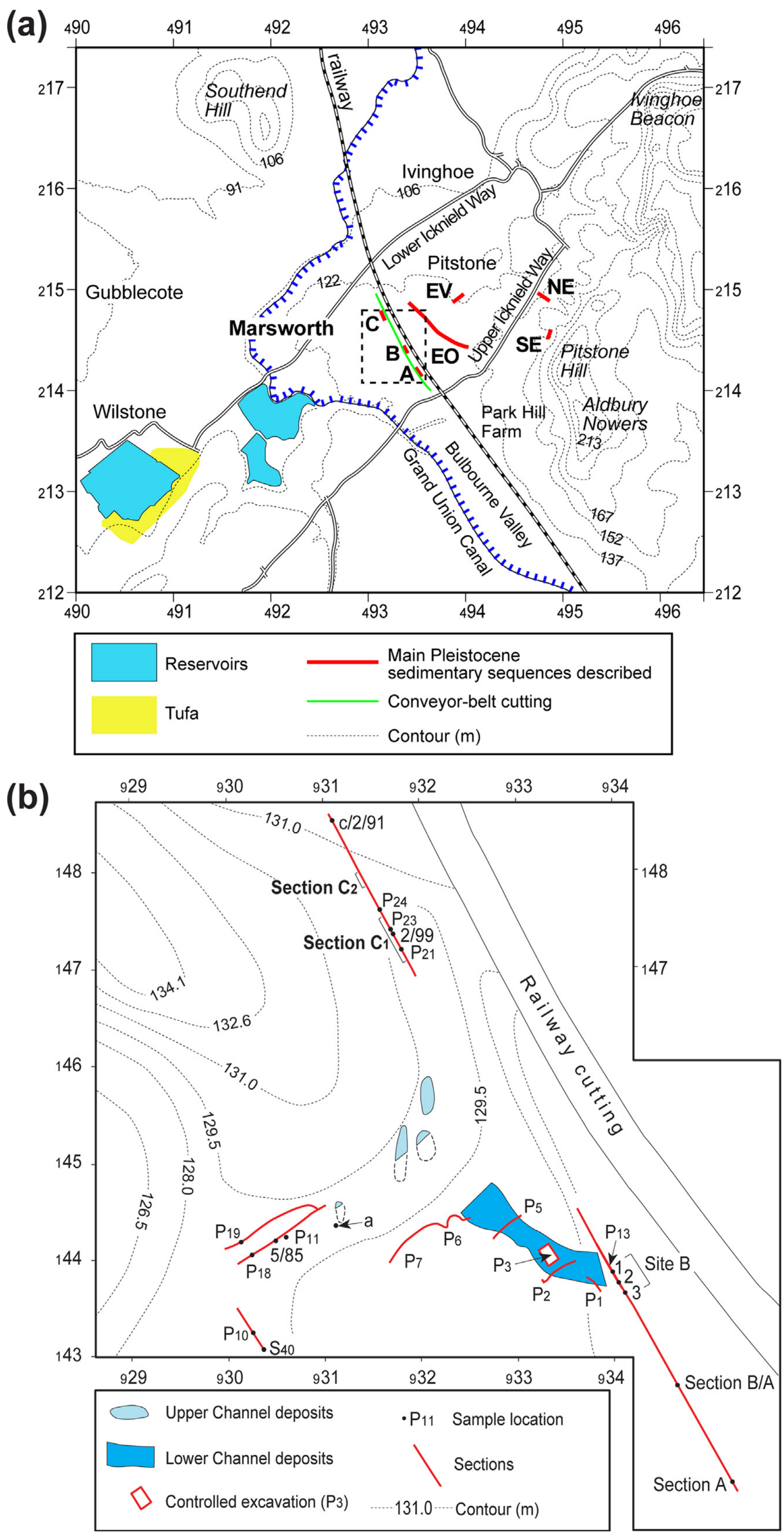

Fig. 2. (a) Location of main Pleistocene sedimentary sequences previously described from near Marsworth: EO = Evans and Oakley's (1952) section in the No. 1 Quarry; NE and SE = Evans' (1966) sections beside Pitstone Hill; EV = Evans and Valentine's (1974) section; Upper and Lower Channels and site B of Green et al. (1984) and Murton et al. (2001). Scale: National Grid at 1 km intervals. Contours in metres. (b) Site plan of sections and sampling points in Pleistocene deposits at the College Lake Wildlife Centre near Marsworth, formerly the No. 3 (Bulbourne) Quarry. Scale: National Grid at 100 m intervals. Location shown by dashed rectangle in (a).

pre-date, the drainage system of the River Thame, a 'subsequent' river which extends into the Vale of Aylesbury (Fig. 1).

Gravel opposite the Tring Gap occurs at Gubblecote (Sherlock, 1922, p. 51), c. 3 km west of the present study site (Fig. 2a). It consists largely of angular flints, rounded pellets of chalk, some Palaeogene flint pebbles, and fragments of Upper Greensand (Oakley, 1936). Poorly sorted and festooned, the gravel has been compared with the 'taele gravels' of Cambridgeshire and attributed to deposition by solifluction and snow meltwater in front of the Chiltern scarp during a late glacial phase (Oakley, 1936). It has also been interpreted as a lacustrine deposit of proglacial Lake Oxford in the Vale of Aylesbury (Harmer, 1907; Sherlock, 1922, 1924). Quartz sand within the gravel is difficult to attribute to local sources and may be of aeolian origin (Avery, 1964, p. 21).

Chalky periglacial slope deposits (coombe deposits or coombe-rock), shown as part of the Valley Gravel in Fig. 1, were described by Evans and Oakley (1952) in Pitstone Quarry to the east of the Marsworth site (EO in Fig. 2a). At Marsworth they occur mainly at the surface, but separate the fills of the Upper and Lower Channels (Green et al., 1984), and therefore date from MIS 6. They are composed mainly of angular chalk and flint clasts derived from the Chiltern scarp slope. Permafrost during MIS 6 at Marsworth is indicated by ice-wedge pseudomorphs penetrating the coombe deposits (Worsley, 1987).

There are no undoubted glacial deposits at the Marsworth study site itself, though Avery (1964, p. 18) recorded a 'brown clay containing scattered subangular flints and quartzose pebbles, resembling Chalky Boulder Clay' on a fan-shaped platform extending east of Marsworth southwards to the gap near Tring Station, and Whiteman (1998) has interpreted a diamicton in the succession we describe as weathered till. Both of these are discussed later.

Nevertheless, definite glacial deposits do occur within a few kilometres of the Marsworth site. The British Geological Survey (BGS) Aylesbury and Hemel Hempstead sheet (238) shows several isolated patches of till and glacial gravel in the Vale of Aylesbury to the west, and a more continuous sheet of till occurs further north, from Leighton Buzzard and Cublington northwards (Fig. 1). The nearest outlier shown on sheet 238 is a very small patch of till on the summit of Southend Hill, approximately 2 km NNW of the Marsworth site (Fig. 2a). The soil here contains flint, quartzite pebbles and other erratics, but further investigation is impossible, because the outlier lies within an Iron Age hillfort under the protection of English Heritage. Near Wingrave, c. 8 km northwest of Marsworth, Avery (1964, p. 18) reported 'typical blue-grey Chalky Boulder Clay', and to the west and north of Leighton Buzzard chalky till is up to 15 m thick and contains rare igneous erratics (Shephard-Thorn et al., 1994). To the northwest of Aylesbury, deposits of till containing quartzose pebbles rarely exceed 1.5 m in thickness and are often strongly weathered (Horton et al., 1995). At Cublington, 11–12 km northwest of the Marsworth site, J. Rose (pers. comm., 2013) has recorded two tills, the lower containing Carboniferous Limestone clasts but no chalk, and the upper with chalk clasts. Rose infers two glacial events at Cublington, the earlier with Carboniferous Limestone derived from the northwest, and the later with chalk derived from the northeast.

The patchy glacial deposits in the Vale of Aylesbury have been attributed to various cold stages. The more continuous sheet north of Leighton Buzzard and Cublington is assigned by the BGS to the Oadby Member of the Wolston Formation (Geology of Britain viewer, 2014), though the small patches of till a few kilometres northeast of Aylesbury are linked to the Lowestoft Formation. The latter is widely equated with the Anglian Stage (MIS 12) (Bowen, 1999), but Sumbler (1995) assigned all glacial deposits near Aylesbury to MIS 10 because of their relationship to the terrace sequence of the River Thame. Keen (1999, 2003), Sumbler (2001), Clark et al. (2004) and Hamblin et al. (2005), all reviewed in Rose (2009), have suggested that the chalky tills of the English Midlands (including the Oadby Till) could date from MIS 10, but this has been questioned by Pawley et al. (2008). A third possibility is that "Wolstonian" ice deposited the Oadby Till during MIS 6 (Jones and Keen, 1993, Fig. 7.3; Gibbard and Clark, 2011).

Similarly, no glacial limits in the Vale of Aylesbury are clearly defined. The Anglian (MIS 12) limit shown by the dashed line in Fig. 1 to the northwest of the Chiltern Hills, based upon Straw and Clayton (1979) and Horton et al. (1995), is very speculative. Although till is thick and continuous only to the west and north of Leighton Buzzard, Shephard-Thorn et al. (1994) inferred an Anglian ice limit impinging on the Chilterns scarp much further east, near Kensworth (c. 10 km ENE of Marsworth), with a lobe extending south-eastwards into the Lea Gap at Luton (Fig. 1). No glacial limits for MIS 10 and 6 have been suggested in the area. Jones and Keen (1993) hypothesised that what is now generally regarded as the Anglian limit in the Vale of Aylesbury dates from MIS 6, but the nearest reasonable evidence for an MIS 6 limit is around the margins of the Fenland Basin, c. 100 km NE of Marsworth (Gibbard et al., 1992, 2009, 2012).

The brown clay 'resembling Chalky Boulder Clay', which Avery (1964) reported on the gently sloping platform fanning out northwestwards from Tring Station to bluffs overlooking the Vale of Aylesbury east of Marsworth, was described as overlying a deposit of 'small subrounded chalk fragments and angular flint chips in a yellowish calcareous matrix', which 'generally has the aspect of Coombe-Rock'. It was shown as Tring series on the 1:63,360 Soil Survey of England and Wales Aylesbury and Hemel Hempstead sheet (238), and was classified as a brown calcareous soil, implying development mainly by decalcification and weathering of a calcareous parent material. The similarity to weathered Chalky Boulder Clay was probably inferred from the clay to clay loam texture and the presence of angular flint fragments, vein quartz and quartzite pebbles. However, flints, quartzose pebbles and hard sandstone clasts were also noted in the underlying coombe rock (Avery, 1964, p. 100), so the brown calcareous soil could have formed by Holocene weathering of the coombe rock, and was not necessarily derived from a separate thin till or other deposit over the coombe rock. In the later rationalisation of soil series (Clayden and Hollis, 1984) the Tring series was renamed Ashley series and, for the purposes of the 1:250,000 National Soil Map (Soil Survey of England and Wales, 1983), was incorporated with various other series into the Charity Association (Jarvis et al., 1984). Much of the land mapped locally as Tring series has since been lost by quarrying of the underlying chalk for the manufacture of cement.

3. Stratigraphy and sedimentology

The Marsworth Pleistocene deposits we describe are at the College Lake Wildlife Centre [SP 933142], formerly the No. 3 (Bulbourne) Quarry of Pitstone Tunnel Cement Ltd, 1–2 km east of Marsworth (Fig. 2a). That part of the quarry containing key stratigraphic sections through the Pleistocene deposits has been designated the Pitstone Quarry Site of Special Scientific Interest (SSSI). As the former quarry developed we have distinguished since the late 1960s sedimentary sections in several areas (Fig. 2b):

(1) The Lower Channel deposits occupy a channel ≤35 m wide that was traced from site B northwestwards for c. 200 m. Sandy gravels in this channel overlie the Zig Zag Chalk Formation of the Grey Chalk Subgroup and contain abundant tufa, bone and ivory fragments, which could be traced with gradually diminishing frequency to point 'a' in Fig. 2b, c. 270 m from site B. The deposits were examined at sections B_{1-3}, P_1, P_2, P_3, P_5

and P_{13}, with a controlled excavation carried out at site P_3 (Figs. 2b and 3; Murton et al., 2001).

(2) The Upper Channel deposits were examined in three small, adjacent areas c. 100–150 m northwest of the northwestern limit of the Lower Channel deposits.

(3) Sections C_1 and C_2 are c. 400–500 m northwest of section B_1, along a conveyor-belt cutting. Stratigraphical continuity was observed neither with site B nor with the Upper Channel deposits because chalk bedrock rises to the surface southeast of section C_1.

(4) Sections B/A and A are c. 132–138 m and c. 252 m, respectively, southeast of section B_1, along the conveyor-belt cutting, which allowed stratigraphic continuity to be observed between these three sequences.

(5) Sections P_6, P_7, P_{10}, P_{11}, P_{18} and P_{19} were examined as the working face of the quarry advanced to the west and northwest.

The deposits of the Lower Channel and Upper Channel were described by Murton et al. (2001). The present paper focuses on the deposits of section C_1 (where we have obtained most samples for dating), supplemented by palaeoenvironmental data from sections C_2, B/A, A, P_6, P_7, P_{10}, P_{11}, P_{18} and P_{19}.

3.1. Description of sections and sediments

3.1.1. Section C_1 (Table 1; Figs. 4a and 5)

Eight stratigraphical units above the Zig Zag Chalk are identified in section C_1. The lowest (unit $C_1$1) is a diamicton, typically clast-supported, with angular to subangular clasts of chalk set in a matrix of finely comminuted chalk. Above it is a discontinuous, massive silty sandy gravel (unit $C_1$2) which rests on a concave-up surface that in places is clearly erosive (−6 to 30 m marks in Fig. 4a). The gravel is overlain by massive clayey silt (unit $C_1$3) containing numerous granules and pebbles of soft, white chalk; in places, the upper c.10–30 cm of the silt has a platy structure of horizontal to subhorizontal partings. Prominent in section C_1 is a pebbly silty clay (unit $C_1$4) ≤c. 1.5 m thick that pinches out at the −5 m, 31 m and 33 m marks. Unit $C_1$5 is a thin discontinuous, mottled pebbly layer containing small chalk fragments and intraclasts similar to the clayey silt of unit $C_1$3. Unit $C_1$6 is a brown silty clay traced between the 17 and 28 m marks, and again between the 35 and 45 m marks. Unit $C_1$7 is a white clayey silt with flint pebbles dispersed throughout it or concentrated in small stringers; the lower contact is sharp to gradational, in places marked by an angular unconformity or overlain by a pebbly lag (e.g. 31.2–33.0 m mark). Unit $C_1$8 is a sand and gravel that is massive to crudely stratified, the lower contact of which is an involuted angular unconformity. Capping the sequence is a soil buried by spoil from excavation of the nearby railway cutting. Further details of the stratigraphy are given in Table 1.

3.1.1.1. Sediment characteristics. Carbonate content of <2 mm fraction (Table 2):

The carbonate contents of fractions <2 mm separated by dry sieving from six samples from section C_1 and one of Zig Zag Chalk (from site B) were determined by calcimeter, measuring the volume of CO_2 at standard temperature and pressure generated by reaction with dilute hydrochloric acid in a closed vessel (Bascomb, 1961).

The Zig Zag Chalk contains 60.5% $CaCO_3$. The two pale coloured clayey silt samples ($C_1$3 and $C_1$7) and the upper sand and gravel ($C_1$8) are all strongly calcareous, but the three samples of silty clay from $C_1$4 and $C_1$6 contain no carbonate.

Particle-size distribution (Table 2):

The particle-size distributions of the same six samples from section C_1 and the Zig Zag Chalk sample were determined by sieving for fractions >63 μm (<+4 ϕ) and pipette sampling for fractions <63 μm (>+4 ϕ), after removal of $CaCO_3$ where necessary by treatment with acetic acid and dispersion in dilute (0.2%) calgon solution.

The acetic acid insoluble residue of the Zig Zag Chalk consists mainly of clay (<2 μm) and coarse silt (16–63 μm) with small amounts of fine silt (2–16 μm) and fine sand (63–250 μm) and traces of medium and coarse sand.

Apart from the upper sand and gravel ($C_1$8), all the samples from section C_1 are rich in clay and also contain moderately large amounts of coarse silt but smaller quantities of fine silt and sand. $C_1$8 contains 45% gravel (>2 mm) in a poorly sorted matrix composed mainly of fine and medium sand (63–500 μm) with smaller amounts of clay, silt of all sizes and coarse sand.

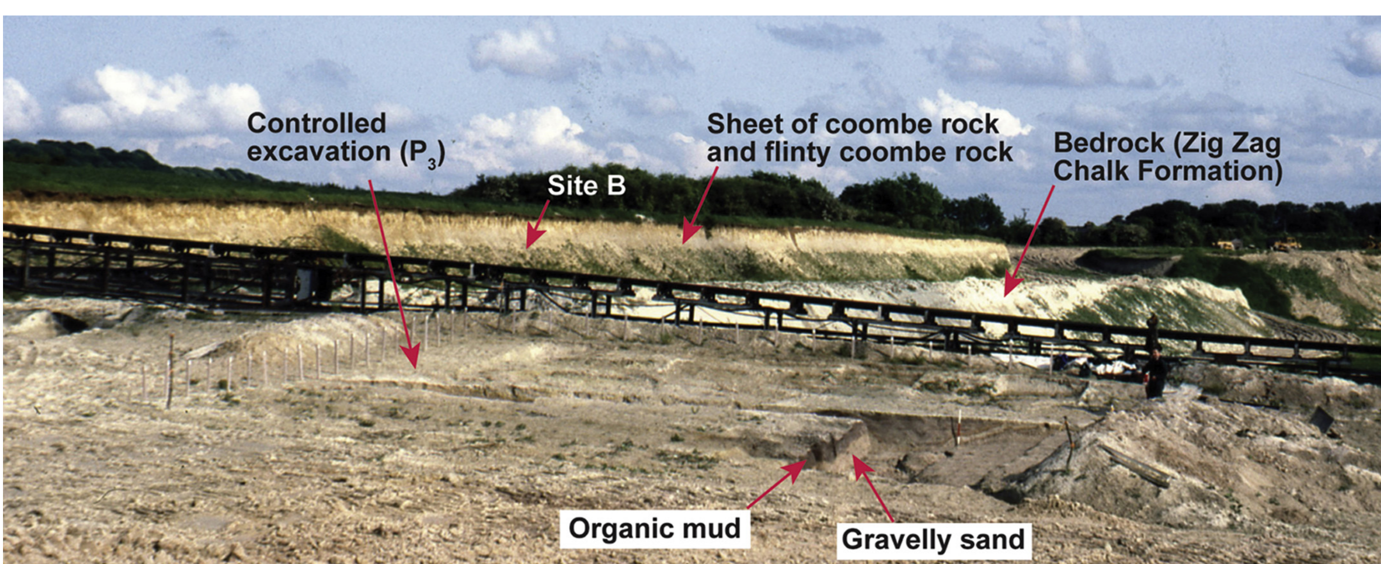

Fig. 3. Lower Channel and overlying periglacial slope deposits exposed in the controlled excavation (P_3) between 1980 and 1984. View looking southeastwards towards the conveyor belt cutting shown in Fig. 2a, with approximate location site B indicated.
David Parish/Buckinghamshire County Museum

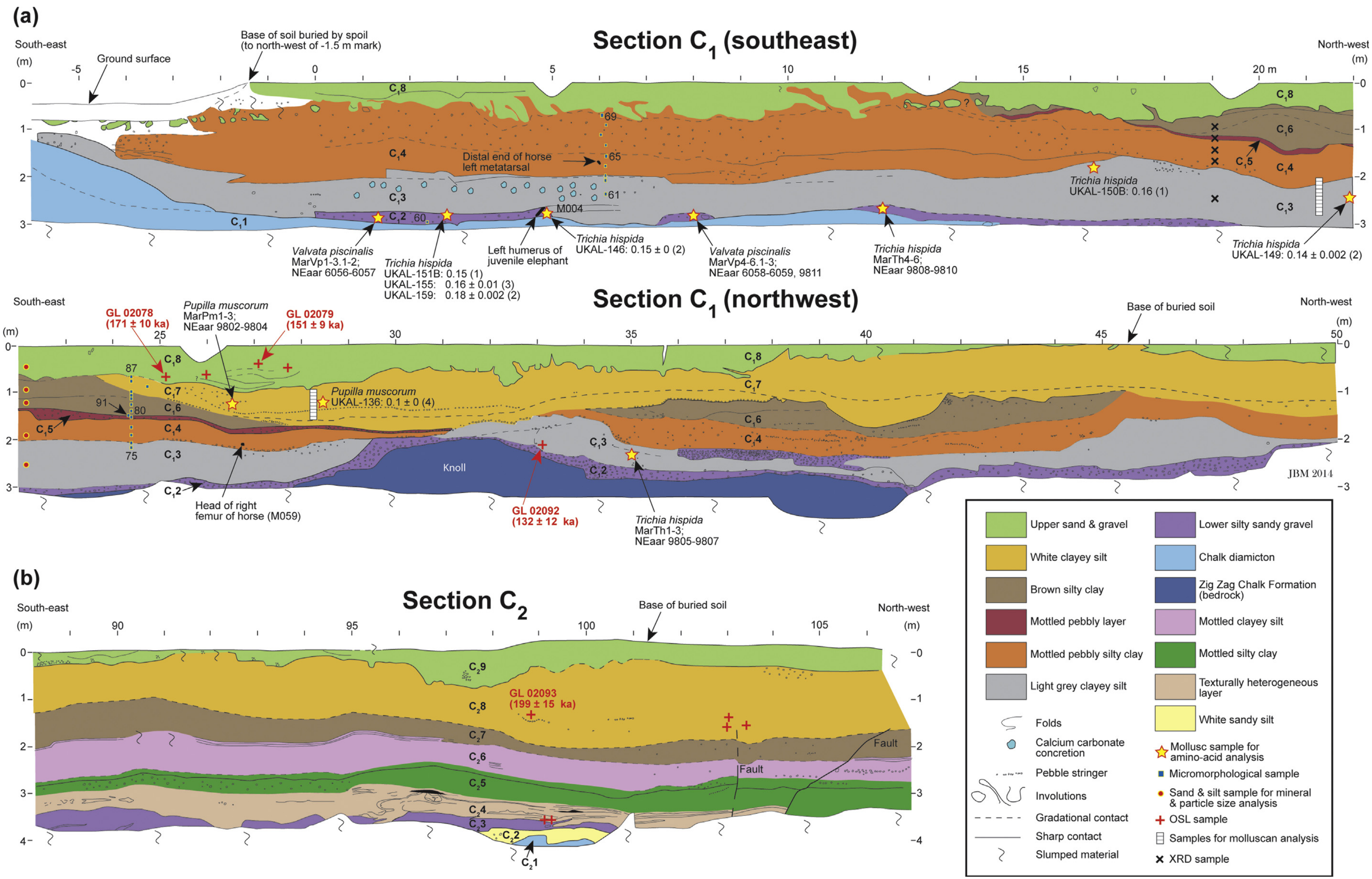

Fig. 4. Stratigraphy of sections C_1 (a) and C_2 (b), recorded in 1995–6. Location shown in Fig. 2b.

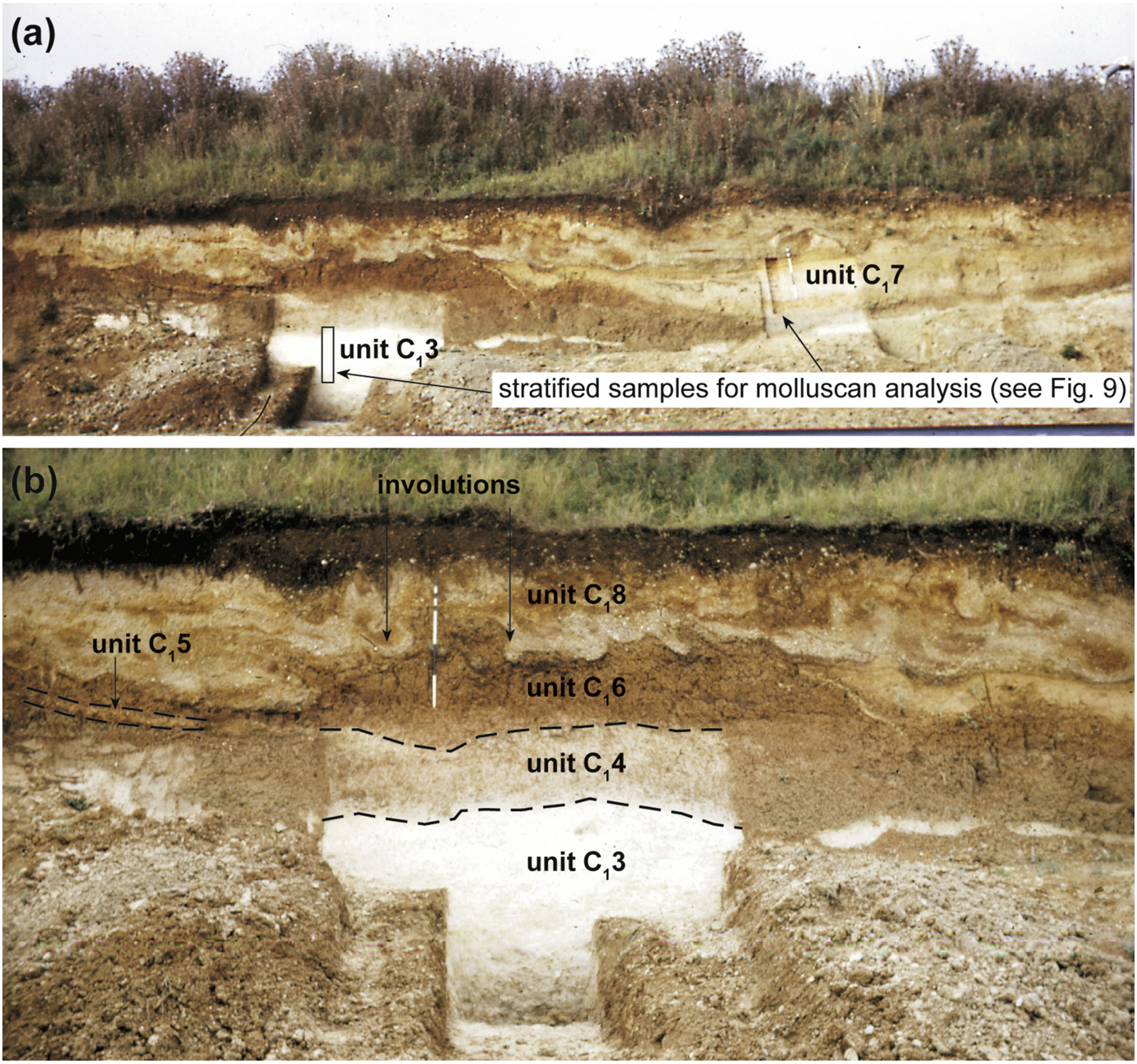

Fig. 5. (a) Section C1 (c. 15–34 m marks on Fig. 4a), photographed in c. 1970. (b) Close-up showing units $C_1$3–8 (c. 17–26 m marks on Fig. 4a). Scales in both are 1 m.

The two samples of strongly calcareous, pale-coloured clayey silt ($C_1$3 and $C_1$7) have approximately similar size distributions to the Zig Zag Chalk and are probably composed mainly of material derived from that formation. However, they both contain slightly more coarse silt than the Zig Zag Chalk, suggesting the presence of a little loess. Units $C_1$4 and $C_1$6 are similar to $C_1$3 and $C_1$7 in size distribution, and could be weathered (decalcified) forms of sediment similar to $C_1$3 or $C_1$7, though they contain more clay and less coarse silt.

Fine sand mineralogy (Table 3):

The fine sand (63–250 μm) fractions of the same samples were separated by decalcification with acetic acid and wet sieving after dispersion in calgon solution. They were then divided into light and heavy minerals by flotation in bromoform (SG 2.9). Both light and heavy minerals were identified by optical properties using a petrological microscope, and percentages in each density fraction were calculated from counts of 500–1500 grains per fraction.

The fine sand of the acetic acid insoluble residue of the Zig Zag Chalk contains 75% quartz, 22% collophane (phosphate of biological origin), 2% limonite/haematite (mainly oxidised glauconite) and trace amounts of fresh (green) glauconite and detrital muscovite, alkali feldspar, zircon, garnet, rutile and chlorite.

The light fractions of the fine sands from all six samples from section C_1 contain more quartz, flint and alkali feldspar than the Zig Zag Chalk. These differences suggest that, whereas the C_1 samples may contain variable amounts of fine sand derived from the Zig Zag Chalk, they also incorporate material from one or more additional sources. The absence of glauconite in, $C_1$3, $C_1$4 and $C_1$6 could be the result of weathering. However, while $C_1$4 and $C_1$6 contain large amounts of limonite/haematite (probably weathered glauconite) in the heavy fractions of their fine sands, $C_1$3, contains relatively

Table 1
Stratigraphy and sedimentology at section C_1.[a]

Unit	Deposit	Description	Interpretation
C_18	Sand and gravel ($\leq$1.0 m thick)	White chalk and flint gravel with sandy lenses; chalk granules and pebbles, soft, white, mostly subangular to rounded; flint granules and pebbles, blue-grey, commonly with white or brown patina, angular to subangular; elongate flint pebbles commonly vertically aligned; few quartzose pebbles, white or orange, subangular to subrounded; variable proportion of sandy matrix; massive to crudely stratified; brownish yellow (10YR 6/8) to yellowish brown (10YR 5/6–8) iron staining common, especially in lower part; locally iron-cemented; lower contact sharp, involuted angular unconformity. (Locally present at the top of the unit is chalk gravel comprising granules and mostly subrounded pebbles ($\leq$2 cm) of chalk and some angular flint; 53% $CaCO_3$ in $\leq$2 mm fraction; thin horizontal stratification)	Meltwater deposit above erosion surface
C_17	White clayey silt ($\leq$1.5 m)	White (10YR 8/1) to light grey (2.5Y 7/2) clayey silt with yellow (10YR 8/6) bands and mottling; few flint pebbles ($\leq$3 cm), blue-grey, typically with white patina, subangular, dispersed or form small stringers or basal lag; numerous calcareous tubes (0.5–2 mm diameter); lower contact gradational to sharp, undulating to irregular, in places an angular unconformity and/or overlain by pebbly lag (e.g. 31.2–33.0 m mark)	Slope deposits (reworked chalky and loess deposits)
C_16	Brown silty clay ($\leq$1.0 m)	Yellowish brown (10YR 5/4–5) pebbly silty clay; massive; flint pebbles, white to orange, angular to subangular; 2 subunits between 18.5 and 26.5 m marks: Upper subunit: weakly calcareous near top, strongly iron stained, mottled yellowish brown (10YR 5/8), brownish yellow (10YR 6/8) and dark yellowish brown (10YR 4/6); locally pale olive (5Y 6/3); flint pebbles, white to orange, mostly angular to subangular; few quartzose pebbles, rounded; granules and small pebbles of white chalk near top; lower contact sharp to gradational, curved Lower subunit: weakly calcareous in basal 2 cm; yellowish brown (10YR 5/4), lower contact sharp to gradational, curved	Weathered soil deformed by periglacial slope processes [alternatively, glacitectonite]
C_15	Mottled pebbly Layer ($\leq$0.15 m)	Light grey to strongly mottled black, strong brown (7.5YR 5/8) and white (5Y 8/2) pebbly deposit with a texturally variable, calcareous matrix of clay, silt and sand; numerous flint pebbles, blue-grey with white patina, angular to subangular; occasional quartzose pebble ($\leq$4.5 cm), rounded; occasional granules and pebbles of white chalk; clayey intraclasts similar to unit C_13; massive; discontinuous layer; passes laterally into underlying mottled silty clay at 22.2 m mark (where the number of clasts significantly decreases), re-appearing at 21 m mark; lower contact sharp to gradational, undulating	Lag deposit [alternatively, glacitectonite]
C_14	Mottled pebbly silty clay ($\leq$1.75 m)	Light grey (2.5Y 7/2) to white (2.5Y 8/2) or pale yellow (2.5Y 7/4) pebbly silty clay, commonly with light yellowish brown (10YR 6/4) and yellowish brown (10YR 5/8) mottles or bands, especially in upper part of unit; flint pebbles, blue-grey or brown with white patina, angular, dispersed; flint granules locally abundant; abundant granules to pebbles of white chalk, subangular to subrounded; occasional quartzose pebble, rounded; massive; calcareous to non-calcareous; abundant calcareous tubes, typically 1 mm diameter; lower contact sharp to gradational, undulating to irregular; between 0 and 17 m marks the lower part of this unit is more silty than the upper part, and between 8 and 17 m marks it grades down into unit C_13	Weathered soil deformed by periglacial slope processes [alternatively, glacitectonite]
C_13	Light grey clayey silt ($\leq$1.5 m)	Light grey (5Y 7/2) to light olive grey (5Y 6/2) or white (5Y 8/1–2) clayey silt; calcareous; numerous granules and pebbles of soft white chalk, rounded to subrounded, dispersed throughout unit; few flint pebbles, blue grey or black $\pm$ white patina, angular to subrounded; occasional ?quartzose pebble, rounded; white calcareous nodules common; fine tubular pores common; fine colour bands (2–20 mm thick) and mottling from iron staining, especially in upper half of unit; platy structure locally present in upper 10–30 cm of unit (horizontal to subhorizontal, wavy, discontinuous or bifurcating partings 2–$\geq$10 cm long connected by vertical to subvertical partings 2–7 mm high); lower contact typically gradational and undulating. (At the top of the unit is a discontinuous layer ($\leq$15 cm thick) of pale olive (5Y 6/3) to pale olive grey (5Y 6/4) clayey silt with numerous granules and small pebbles of white chalk; branching, white tubes; iron-stained bands; gradational lower contact)	Slow flowing stream that infilled with sediment and became marshy
C_12	Silty-sandy gravel ($\leq$40 cm)	Pebbles of flint (black to blue grey $\pm$ white patina, angular to subangular), light grey chalk (rounded to subrounded) and quartzose rock (rounded); matrix of sandy silt; irregularly developed layer; massive; lower contact sharp to gradational, irregular and commonly iron-stained; between the 36 and 40 m marks, the gravel forms a lens whose lower contact is sharp and irregular above light grey clayey silt	Fluvial deposit above erosion surface
C_11	Chalk diamicton ($\geq$1 m)	Light grey (5Y 7/2), coarse diamicton, with angular to subangular chalk clasts (<1 to 20 cm maximum dimension) in pasty chalk matrix; surfaces of clasts commonly blackened (with ?manganese); massive; typically clast-supported, locally matrix-supported; upper contact rises to present ground surface southeast of–6 m mark (Fig. 4a), where a thin, modern soil has developed on it	Periglacially-disturbed bedrock

[a] Sections C_1 and C_2 underlie a palaeosol (*c.* 0.1–0.3 m thick) buried during Victorian times by spoil (*c.* 0.5–2.0 m thick) excavated from the nearby railway cutting (Fig. 2b). Beneath the palaeosol are some V- and U-shaped features filled with sandy or clayey loam or chalk gravel. Those features with clay linings are probably of solutional origin, but the origin of the others is unclear; some may represent the boundary ditches of prehistoric or Roman field systems.

little. The abundance of collophane in C_13, C_17 and C_18 agrees with the large carbonate contents in suggesting a major Zig Zag Chalk component of these units. The small amounts of collophane in samples C_14 and C_16 may suggest a source other than the chalk, though collophane could have been partially removed by acid weathering during or since deposition.

The fine sand component that is not derived from the Zig Zag Chalk contains quartz and flint in the light fraction, and magnetite, leucoxene, apatite, zircon, tourmaline, epidote, garnet, yellow, brown and red rutiles, anatase and green hornblende in the heavy fraction. Possible sources include Palaeogene material incorporated in the clay-with-flints or Quaternary deposits of mixed local and far-travelled material, such as glacial sediments or the coarse fraction of loess. However, the component is not as mineralogically diverse as the assemblages in the various tills of eastern England.

Coarse silt mineralogy (Table 4):

Coarse silt (16–63 μm) from the same samples was separated from their non-calcareous (acetic acid-insoluble) residues by repeated sedimentation in aqueous suspension, and then divided into light and heavy fractions by centrifugation in bromoform

Table 2
Particle-size distributions (carbonate-free basis) and carbonate contents of samples from Section C_1 and of Zig Zag Chalk from site B.

	Φ Divisions	μm equivalent	Light grey clayey silt $C_1$3	Mottled pebbly silty clay $C_1$4	Brown silty clay $C_1$6	Brown silty clay $C_1$6	White clayey silt $C_1$7	Upper sand and gravel $C_1$8	Zig Zag Chalk, Site B
Gravel	<−1	>2000	0.0	0.3	0.0	0.0	0.0	45.2	0.2
Sand	0 to−1	1000–2000	0.0	0.1	0.1	0.3	0.0	2.4	0.3
	1 to 0	500–1000	0.0	0.4	0.6	2.8	0.0	4.2	0.4
	2 to 1	250–500	0.2	1.3	3.5	6.3	0.6	10.4	0.5
	3 to 2	125–250	1.0	1.1	3.4	3.4	0.9	10.2	2.4
	4 to 3	63–125	2.9	2.3	2.7	2.7	3.2	3.2	6.2
Silt	5 to 4	31–63	17.4	12.0	7.6	7.8	14.6	4.9	10.1
	6 to 5	16–31	22.4	15.6	10.4	11.2	18.8	4.0	16.0
	7 to 6	8–16	8.8	9.6	9.4	7.3	12.4	2.5	8.2
	8 to 7	4–8	4.1	6.1	5.6	5.3	8.0	2.6	5.2
	9 to 8	2–4	7.5	7.0	4.1	4.3	4.2	3.1	3.1
Clay	>9	<2	35.7	44.2	52.6	48.6	37.3	7.3	47.4
Carbonate %			65.0	0.0	0.0	0.0	50.8	37.9	60.5

Sample locations for C_1 shown in Fig. 4a

(SG 2.9). The heavy fractions were frozen in the base of the centrifuge tubes using an ice–salt mixture, thus allowing the floating light fractions to be poured off, filtered and washed. Minerals present in the two fractions were identified by their optical properties using a petrological microscope, and percentages were calculated from counts of 500–1500 grains per fraction.

The coarse silt from the Zig Zag Chalk sample consists mainly of quartz, with larger amounts of alkali feldspar, muscovite and glauconite but less collophane than occurs in the fine sand. The heavy fraction also contains a wider range of detrital minerals than the fine sand.

In section C_1, the two calcareous units ($C_1$3 and $C_1$7) contain decalcified coarse silt fractions that resemble in mineralogical composition the decalcified coarse silt of the Zig Zag Chalk. They contain more alkali feldspar than the chalk and this could be derived from a Pleistocene (loess or glacial) source.

The coarse silt of units $C_1$4 and $C_1$6 is distinguished from that of $C_1$3 and $C_1$7, by a distinctly different collophane content. This could have been lost from $C_1$4 and $C_1$6 by acid weathering. All the C_1 samples contain components derived from sources other than the Zig Zag Chalk. The coarse silt from $C_1$8 (upper sand and gravel) differs from that of the other C_1 units mainly in containing more

Table 3
Mineralogy of the fine sand fraction (63–250 μm), section C_1. Light minerals given as percentages of fine sand; heavy minerals as parts per thousand (‰) of heavy fraction.

Layer		Zig Zag Chalk, Site B	Light grey clayey silt	Mottled pebbly silty clay	Brown silty clay	Brown silty clay	White clayey silt	Upper sand and gravel
Unit			$C_1$3	$C_1$4	$C_1$6	$C_1$6	$C_1$7	$C_1$8
Light fraction								
Quartz	%	75	85	83	88	94	85	91
Alkali feldspar	%	<1	5	9	6	1	8	4
Flint	%	–	4	2	4	1	1	1
Chalcedony	%	–	4	6	1	<1	3	–
Muscovite	%	<1	–	–	–	–	1	–
Glauconite	%	<1	–	–	–	–	<1	2
Heavy fraction	%	24.0	1.8	0.4	0.4	3.5	1.8	2.3
Limonite/haematite	‰	89	6	326	654	742	100	718
Magnetite	‰	–	4	255	95	97	32	55
Leucoxene	‰	–	27	84	33	28	26	14
Pyrite	‰	–	–	–	–	–	–	–
Collophane	‰	904	920	5	105	4	780	157
Apatite	‰	–	9	2	2	2	2	1
Zircon	‰	3	23	116	25	38	12	20
Tourmaline	‰	–	1	31	20	17	6	8
Epidote	‰	–	3	37	8	17	5	1
Zoisite	‰	–	–	4	–	2	1	–
Garnet	‰	1	–	76	29	28	8	12
Yellow rutile	‰	–	2	5	2	2	1	2
Brown rutile	‰	1	–	15	5	4	1	3
Red rutile	‰	1	–	4	1	2	–	1
Anatase	‰	–	4	1	1	2	1	–
Brookite	‰	–	–	1	–	–	–	–
Green hornblende	‰	–	–	10	6	5	1	1
Tremolite/actinolite	‰	–	–	–	1	1	–	–
Chlorite	‰	1	1	1	–	–	21	–
Biotite	‰	–	–	–	–	–	1	–
Staurolite	‰	–	–	18	10	6	1	3
Kyanite	‰	–	–	9	3	3	1	4
Augite	‰	–	–	–	–	1	–	–

Sample locations shown in Fig. 4a, except for Zig Zag Chalk and unit $C_1$7.

Table 4
Mineralogy of the coarse silt fraction (16–63 μm), section C_1. Light minerals given as percentages of coarse silt; heavy minerals as parts per thousand (‰) of heavy fraction.

Layer		Zig Zag Chalk, Site B	Light grey clayey silt	Mottled pebbly silty clay	Brown silty clay	Brown silty clay	White clayey silt	Upper sand and gravel
Unit			C_13	C_14	C_16	C_16	C_17	C_18
Light fraction								
Quartz	%	90	91	90	93	89	88	84
Alkali feldspar	%	3	8	8	6	9	10	7
Flint	%	1	<1	1	<1	1	–	<1
Muscovite	%	4	<1	–	–	<1	<1	6
Glauconite	%	2	1	1	1	<1	1	3
Heavy fraction								
Limonite/haematite	‰	205	37	201	168	412	219	605
Magnetite	‰	84	91	156	304	179	148	70
Leucoxene	‰	85	177	289	140	156	141	69
Collophane	‰	410	372	–	14	–	258	115
Apatite	‰	1	1	–	–	–	1	1
Zircon	‰	112	147	153	220	131	89	46
Tourmaline	‰	5	25	23	12	7	13	18
Epidote	‰	18	30	59	41	41	40	15
Zoisite	‰	1	5	2	3	5	4	2
Garnet	‰	–	13	15	11	3	14	8
Yellow rutile	‰	53	40	38	34	24	17	13
Brown rutile	‰	–	11	10	7	3	3	3
Red rutile	‰	–	–	–	1	1	–	1
Anatase	‰	19	32	30	21	20	11	10
Brookite	‰	3	4	4	3	2	1	2
Green hornblende	‰	–	2	5	5	2	10	1
Tremolite/actinolite	‰	–	1	3	3	1	4	1
Chlorite	‰	2	8	11	8	12	26	17
Biotite	‰	2	–	–	–	1	1	1
Staurolite	‰	–	1	1	3	–	–	1
Kyanite	‰	–	3	–	1	–	–	–
Siderite	‰	–	–	–	–	–	–	1
Sphene	‰	–	–	–	1	–	–	–

Sample locations shown in Fig. 4a, except for Zig Zag Chalk and unit C_17.

muscovite, glauconite and limonite/haematite (weathered glauconite), all which could have been derived from the Zig Zag Chalk.

Clast lithology (Table 5):

Four gravel-rich samples were collected from section C_1 and the 8.0–11.2 mm and 11.2–16.0 mm size fractions were analysed following Green and McGregor (1978). Local clasts dominate all four samples. Flint is the most common component and constitutes almost all of a gravelly seam sampled from unit C_14. Most of the flint is sub-angular and probably derived entirely from the White Chalk Subgroup, but a few pieces of well-rolled, chatter-marked flint pebbles may derive from Palaeogene pebble beds above the Chalk. The other local components are chalk pebbles and ferruginous concretions. The latter includes pieces of pyrite nodule probably derived from the Grey Chalk Subgroup, and pieces of iron-cemented sandstone possibly derived from Palaeogene beds, from residual deposits above the Chalk or from Mesozoic deposits. The only other local components are small phosphatic nodules in unit C_12, probably from the Zig Zag Chalk, and a few small pieces of tufa in the same sample. Non-local lithologies in all four samples comprise mainly sandstone and quartzite pebbles, many of them well-rounded. Cherts of indeterminate provenance also occur in all four samples, though *Rhaxella* chert was identified in the sample from unit C_18. Quartz occurs in all but unit C_14 and limestone clasts occur in samples from unit C_12 and the gravel at the top of unit C_13.

Units C_12 and C_13 are generally similar in character except that unit C_12 has a substantial chalk content, consistent with its position resting directly on the Zig Zag Chalk. Gravel at the top of unit C_13 is probably a lag on the surface of this unit. The similarity of the two gravel deposits suggests that units C_12 and C_13 are closely related. The presence of tufa clasts in unit C_12 indicates the proximity of conditions similar to those represented at site B (Murton et al., 2001) and suggests that units C_12 and C_13 are at least partly the deposits of a spring-fed water body. The far-travelled material in the two samples shows similar quartz/other far-travelled ratios, and both samples include quartzites that resemble types common in the Kidderminster Conglomerate of the Midlands. A possible origin for the far-travelled lithologies in units C_12 and C_13 is material introduced by Anglian ice.

Unit C_18 has a composition broadly similar to units C_12 and C_13, but with only about half as much far-travelled material relative to local components. The far-travelled material resembles in composition units C_12 and C_13 but includes pebbles of *Rhaxella* chert. As this lithology was introduced in significant amounts into parts of southern England by Anglian glacial ice, it is likely that the far-travelled clasts in unit C_18 are of this origin.

3.1.2. *Section C_2 (Table 6; Fig. 4b)*

Section C_2 is c. 38–56 m northwest of section C_1 (Fig. 2a). At its base a diamicton of Zig Zag Chalk (unit C_21) is overlain by a white sandy silt (unit C_22) that is calcareous and contains a few flint and occasional quartzose pebbles. Unit C_23 is a sand and gravel with pebbles of flint, grey chalk and quartzose rock. Unit C_24 is a texturally heterogeneous deposit (sand, silt and clay) with wavy streaks of silt and clay, irregular lenses of sandy gravel, recumbent folds and boudinage structures. Unit C_25 is a mottled silty clay with sand- to pebble-size fragments of white chalk. Above it, a mottled clayey silt (unit C_26) grades upward into a silt and silty sand that is locally stratified at the top. Unit C_27 is a brown silty calcareous clay with numerous sand-size fragments of white chalk, occasional stringers of granules and a few flint pebbles. It grades upward into a white clayey silt (unit C_28) containing granules to small pebbles of white chalk and flint pebbles; some pebbles occur as stringers, one of which has a concave-up form (99 m mark, Fig. 4b). The uppermost deposit is a sandy gravel (unit C_29) with abundant flint pebbles, numerous quartz pebbles and some silty beds; its base is sharp and irregular, in places with a

Table 5
Clast lithology of gravel samples from section C_1 (Mw/G1–4), in stratigraphic order from highest to lowest, and sample S40 at section P_{10}.

Stratigraphic unit	Sample	Chalk	Flint	Iron	Phos.	Tufa	Qtz	Qzite	Sst	Lst	Chert	Rhax	Misc	*n*	qz/o	% far
C_18	Mw/G3	19.2	70.3	3.0	–	–	1.5	3.0	2.3	–	0.4	0.4	–	266	0.25	7.5
		39.6	48.2	6.8	–	–	0.7	3.2	–	–	–	0.4	1.1	280	0.15	5.4
Gravelly seam within C_14	Mw/G4	–	98.9	0.4	–	–	–	0.4	0.4	–	–	–	–	287	–	0.7
		1.2	96.4	1.2	–	–	–	0.8	–	–	0.4	–	–	251	–	1.2
Gravel at top of C_13	Mw/G2	1.0	78.7	4.6	–	–	4.0	6.7	2.9	0.4	1.0	–	0.4	475	0.34	15.6
		7.5	72.0	9.7	–	–	4.1	1.6	3.4	–	0.9	–	0.6	318	0.62	10.7
C_12	Mw/G1	29.6	56.9	1.0	–	–	3.6	6.4	1.8	0.3	0.3	–	–	385	0.41	12.5
		34.1	54.2	2.1	1.7	1.1	2.1	2.3	1.1	–	0.6	–	0.6	522	0.46	6.7
Section P_{10}	S40	33.0	37.3	4.6	–	–	1.7	9.9	9.7	2.7	0.8	0.2	–	475	0.07	25.0

For all samples except S40, 11.2–16 mm (upper row) and 8.0–11.2 mm (lower row) showing per cent composition, quartz/other far-travelled ratio (qz/o), and per cent far-travelled (% far). S40: 11.2–16.0 mm only. Abbreviations: Iron: iron cemented sandstone and ferruginous nodules; Phos: phosphatic nodules; Qtz: quartz; Qzite: quartzite; Sst: sandstone; Lst: limestone; Rhax: *Rhaxella* chert; Misc: miscellaneous (igneous, metamorphic, schorl); *n*: sample size.

channel-like form (e.g. 96–99 m marks, Fig. 4a). An upper sub-unit comprises fine gravel with granules to 1 cm pebbles of white chalk and occasional flint.

3.1.3. Section B/A (Table 7; Fig. 6)

At section B/A the Zig Zag Chalk is brecciated to depths of at least 2 m beneath the Pleistocene deposits. The brecciation (unit B/A1) comprises mostly tabular, subangular blocks with 'matched' sides. Some blocks, particularly towards the top of the brecciated chalk, are partially or completely surrounded by powdery chalk. As the proportion of powdery chalk matrix increases and the number of matched sides decreases, the brecciated chalk grades upwards into white coombe rock (unit B/A2). Two subunits of coombe rock are distinguished, the lower with larger chalk blocks (≤12 cm diameter) than the upper (≤4 cm) and lacking the few flint pebbles found in the upper. Above it is a flinty coombe rock (unit B/A3) that

Table 6
Stratigraphy and sedimentology at section C_2.

Unit	Deposit	Description	Interpretation
C_29	Upper gravel	Upper subunit (10–15 cm thick): white chalk gravel (granules to 1 cm pebbles) with occasional flint pebbles Lower subunit ≤c. 0.8 m thick): sandy gravel with abundant flint pebbles and numerous, rounded quartzose pebbles; some silty beds; lower contact sharp and irregular	Meltwater deposit above channelled erosion surface
C_28	White clayey silt (≤1.9 m)	White (10YR 8/2) clayey silt (cf. unit C_17); calcareous; numerous flint pebbles, angular to subangular, in upper 15–30 cm; granules to small pebbles of white chalk and subangular orange-white pebbles of flint are mostly dispersed in silt; few pebble stringers, one of which has a small, concave-up form (99 m mark); *Pupilla muscorum* common; lower contact gradational and undulating	Slope deposit (reworked chalky material and loess)
C_27	Brown silty clay (≤0.8 m)	Faintly mottled yellowish brown (10YR 5/4) and brownish yellow (10YR 6/8) silty clay to clayey silt; lateral colour change to brown (10YR 5/3); calcareous; few subangular orange-white flint pebbles and numerous coarse sand-size fragments of white chalk; occasional stringer of granules; massive; lower contact gradational and undulating	Slope deposit
C_26	Mottled clayey silt (≤0.8 m)	Light olive grey (5Y 6/2) massive clayey silt with fine yellowish brown (10YR 5.5/8) mottles, grading up into pale olive (5Y 6/3) silt and sandy silt; some flint pebbles; locally stratified at top of and within unit; strata are a few mm to 4 cm thick, parallel, horizontal to gently dipping, with sharp irregular lower contact with 1 cm relief; coarse sand grains (plus few granules of white chalk and occasional small pebble) are concentrated in one 1–2 cm thick stratum; calcareous; *Pupilla muscorum*; lower contact gradational and undulating	Slope deposit (undisturbed strata attributed to sheetwash)
C_25	Mottled silty clay (≤0.6 m)	Light olive grey (5Y 6/2) silty clay with brownish yellow (10YR 6/8) to yellowish brown (10YR 5/8) mottles; calcareous; massive; numerous sand to small pebble-size fragments of white chalk; abundant pebbles (≤5 cm) of white chalk and flint between 89 and 95 m marks; lower contact gradational and undulating	Slope deposit
C_24	Texturally heterogeneous layer (≤1.0 m)	Variable unit comprising: (1) reddish yellow (7.5YR 7/8) fine to coarse granuley sand, massive, calcareous; coarse sand grains of white chalk, grey chalk and flint; lens *c.* 0.5–7 cm thick and *c.* 1 m wide; (2) light grey (5Y 7/2) silt with yellow (10YR 8/8) and brownish yellow (10YR 6/8) fine mottles and streaks; calcareous, massive; contains granules and small pebbles of white chalk; and (3) brown (10YR 5/3) clay with yellowish brown (10YR 5/8) mottles; calcareous; contains granules of white chalk; forms elongate lenses, two of which show boudinage. Unit contains numerous horizontal to subhorizontal, wavy streaks of silt and clay, irregular lenses of sandy gravel and occasional recumbent folds; lower contact sharp and irregular	Weathered soil deformed by periglacial slope processes [alternatively, glacitectonite]
C_23	Lower sand and gravel (<1–50 cm)	Mainly granule to pebble gravel with silty sandy matrix; abundant angular to subrounded flint pebbles (white or blue-grey with white patina, ≤5.5 cm); abundant granule- to pebble-size blocks of grey chalk; rounded to subrounded quartzose pebbles; crudely stratified, with horizontal to subhorizontal strata typically 1–3 cm thick; calcareous; variable thickness; lower contact sharp and irregular	Fluvial deposit
C_22	White sandy silt (≤35 cm)	White (5Y 8/1.5) fine to very fine sand and silt; massive; few pebbles, especially near base, subangular to subrounded flint (blue grey with white patina; white; orange-brown); occasional quartzose pebble (≤7 cm); calcareous; lower contact sharp and irregular	Fluvial deposit
C_21	Chalk diamicton	Coarse diamicton comprising blocks of grey chalk set in a matrix of pasty chalk; massive	Periglacially-disturbed bedrock

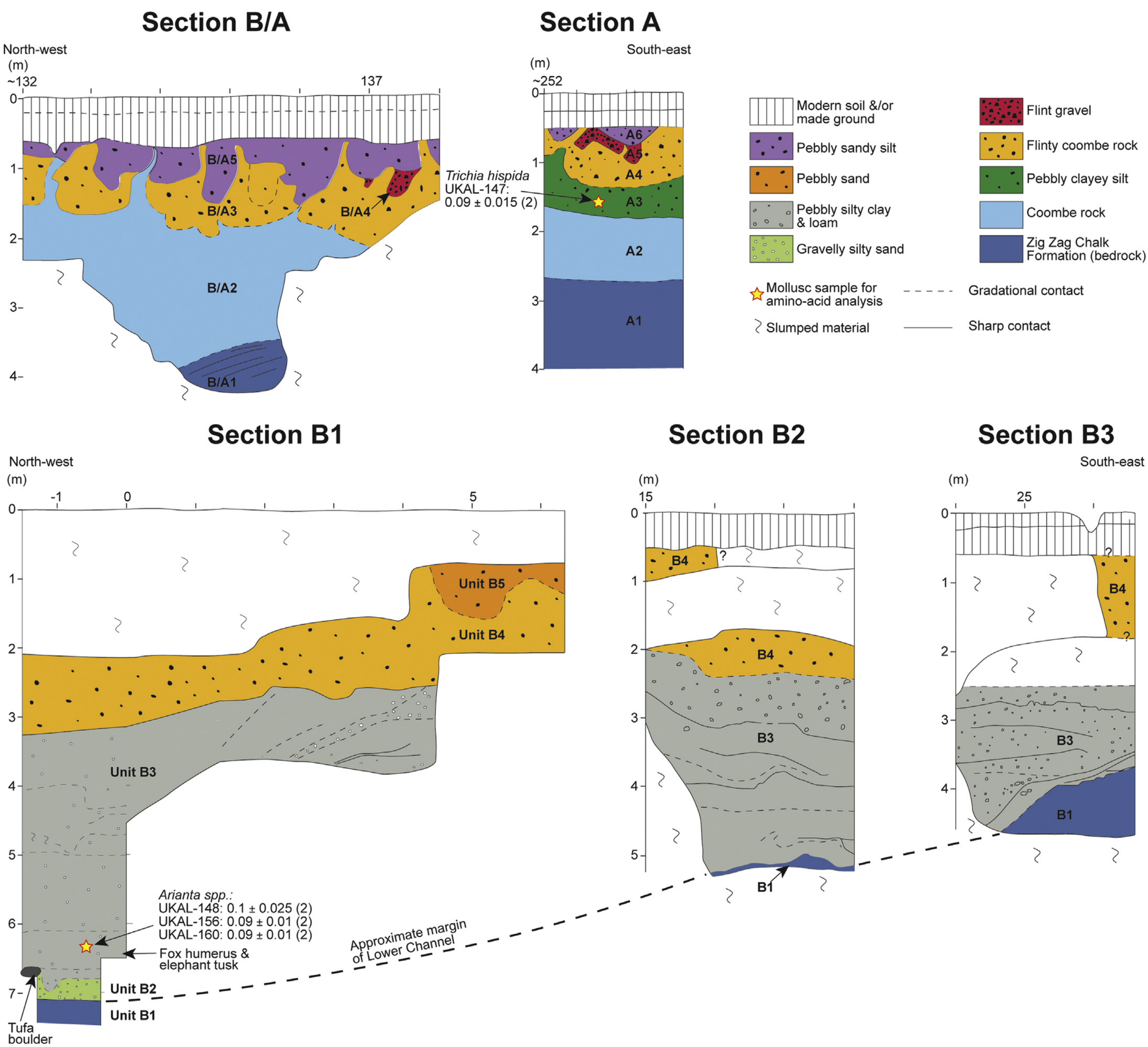

Fig. 6. Stratigraphic sections at sections A and B/A, and site B. Locations shown in Fig. 2b. Sections B1–B3 modified from Murton et al. (2001)

is distinguished from unit B/A2 by its much higher concentration of flint pebbles and cobbles and yellow to very pale brown colour. Both the flinty coombe rock and the upper subunit of the underlying coombe rock are involuted into a flint gravel (unit B/A4) and pebbly sandy silt (unit B/A5). The gravel comprises angular to rounded flint pebbles and cobbles in a matrix of sandy silt, and is preserved only within the involutions. The overlying pebbly sandy silt is massive and contains chalk and flint granules and pebbles in a sandy silt matrix.

3.1.4. Section A (Table 8; Fig. 6)

The sediments at section A resemble those at section B/A, with the addition of a pebbly clayey silt (unit A3) filling a depression between the coombe rock (unit A2) and flinty coombe rock (unit A4). The silt contains numerous angular to subangular flint pebbles, and rhizoliths.

3.1.5. Sections P_6, P_7, P_{10}, P_{11}, P_{18} and P_{19} (Fig. 2b)

During working of the former quarry, sand and gravel similar to that in the Lower Channel were observed to overlie bedrock over a wide area in the eastern part of the quarry. Loams rested, without any obvious unconformity, on the sand and gravel at the S40 sample point and more generally in the eastern part of the quarry. The loams resembled the white clayey silt in the upper part of sections C_1 and C_2. Near the northern limit of quarrying, the loams rested on an erosional surface that truncated a channel infill.

Sample S40 came from sands and gravels c. 3.0 m thick at section P_{10}, where the bedrock level was at 123.3 m OD (Fig. 2b). The gravel formed part of a succession of sands and gravels which had been traced across the quarry from site B. The clast lithology of sample S40 resembles that of units C_12 and C_13 from section C_1 (Table 5), but contains a larger proportion of far-travelled material: mainly quartzite and sandstone (78%), with some *Rhaxella* chert.

Table 7
Stratigraphy and sedimentology at section B/A.

Unit	Deposit	Description	Interpretation
B/A5	Pebbly sand silt (≤*c.* 0.6 m thick)	Yellow (10YR 7/6) to brownish yellow (10YR 6/6–6/8); mottled, massive, calcareous; abundant chalk granules and pebbles, white to grey, subangular to subrounded; flint pebbles, orange and white, angular to subangular, common; matrix-supported; porous; occasional calcium carbonate nodule; occurs within involutions	Slope deposit, incorporating ?loess
B/A4	Flint gravel (≤*c.* 0.5 m)	Flint pebbles and small cobbles (≤8 cm), orange and white, angular to rounded; matrix of sandy silt similar to overlying unit; lower contact sharp; occurs within involutions	Fluvial deposit (flints reworked from B/A3)
B/A3	Flinty coombe rock (≤*c.* 1.0 m)	Yellow (10YR 8/6) to very pale brown (10YR 8/4); massive; calcareous; sandy silty matrix; matrix- to clast-supported; variable clast density; abundant flint pebbles and cobbles (≤10 cm), blue-grey ± white patina (brown flints less common) angular to subangular; chalk granules and pebbles, hard white and softer grey, subrounded to subangular; lower contact sharp to gradational; involuted	Solifluction deposit (flints derived from white chalk on Chiltern scarp)
B/A2	Coombe rock (≤2.5 m)	Upper subunit: massive chalk diamicton with chalky matrix between white (5Y 8/2) and light grey (5Y 7/2); matrix- to clast-supported; chalk granules to pebbles (≤4 cm), mainly light grey, some white, subangular to subrounded; few flint pebbles, white or blue-grey, angular to subangular; forms involutions; few decimetres thick; lower contact gradational (downward increase in block size and disappearance of flint and white chalk); involuted Lower subunit: massive chalk diamicton with white (5Y 8/2) chalky matrix, distinctly greyer and more olive than underlying chalk, and contains more matrix; silty; massive; blocks of chalk (≤12 cm), subangular to subrounded; matrix- to clast-supported; lower contact gradational	Solifluction deposit (paucity of flints suggests local derivation)
B/A1	Zig Zag Chalk Formation	White (5Y 8/1–2), hard, broken into subangular blocks (≤19 cm), commonly platy, many with 'matched' sides; horizontal joint spacing commonly 2–5 cm, vertical joint spacing commonly several to 10 cm; powdery chalk between blocks	Brecciation due to ice segregation

Table 8
Stratigraphy and sedimentology at section A.

Unit	Deposit	Description	Interpretation
A6	Pebbly sandy silt (≤c. 0.3 m thick)	Mottled pale yellow (2.5Y 7/4) to yellow (10YR 7/6); massive, calcareous; abundant sand to small pebble-size chalk fragments, white, hard, subangular to subrounded; few flint pebbles, orange-brown, angular to subangular; within involutions	Slope deposit
A5	Flint gravel (c. 0.3 m)	Similar to unit B/A4	Fluvial deposit (flints reworked from B/A3)
A4	Flinty coombe Rock (≤c. 0.6 m)	Very pale brown (10YR 8/4) to yellow (10YR 7/6) or brownish yellow (19YR 6/6) flinty chalk diamicton, massive; compositionally heterogeneous: chalky to flinty end members; abundant flint clasts (≤ 14 cm), dark blue-grey and orange-brown, angular to rounded; abundant white chalk granules and pebbles, subangular to subrounded, hard; matrix- to clast-supported; sandy silt matrix (?loessic component); more compact than coombe rock below; involuted	Solifluction deposit (flints derived from white chalk on crest of Chiltern scarp)
A3	Pebbly clayey Silt (0.5 m)	Light grey to light olive grey (5Y 7/2–6/2) massive pebbly calcareous clayey silt; numerous flint pebbles (≤3 cm), blue-grey, angular to subangular, with patchy white patina, matrix-supported; calcareous rhizoliths; white chalk pebbles and flints (≤8.5 cm) towards top of unit; greenish grey chalk pebbles, subangular to subrounded, common in basal 10–15 cm of unit; Mollusca numerous and well preserved; lower contact sharp to gradational and irregular; occupies a filled depression *c.* 100 m wide	Marsh deposit
A2	Coombe rock (c. 1.5 m)	White to light grey (5Y 7/2–8/1–2) massive, matrix-supported chalk diamicton; blocks of light grey chalk (≤3 cm), subangular (no white chalk); small amount of flint; lower contact gradational	Solifluction deposit (paucity of flints suggests local derivation)
A1	Zig Zag Chalk Formation	White (5Y 8/1), highly brecciated to at least 5 m depth; blocks 2–10 cm in maximum dimension, not clear if in situ or moved slightly; some blocks to at least 4 m depth are surrounded by powdery chalk matrix; occasional brown, iron-stained (?marcasite) nodule	Brecciation due to ice segregation

Quartz is a minor component and the quartz/other far-travelled ratio (0.07) is low. The far-travelled material is probably derived from the same (?glacial) source as in samples C_12,C_13 and C_18.

3.1.6. Lower Channel and site B (Figs. 3 and 6)

The Lower Channel deposits in the controlled excavation (P_3) and the sediments nearby from sections B_{1-3} are shown in Figs. 3 and 6 for comparison with the sequences described above. Details are given by Murton et al. (2001).

3.2. Correlation of sediments between section C_1 and the other sections

Several correlations are clear between section C_1 and other sections. The chalk diamicton of unit C_11 correlates with that of unit C_21 and the coombe rock that forms the lower subunit of unit B/A2 and the lower part of unit A2; all comprise chalk clasts set within a powdery chalk matrix, and lack flints. The lower silty sandy gravel of unit C_12 correlates with gravel of unit C_23, the white clayey silt of unit C_17 correlates with that of C_28, and the upper sand and gravel of unit C_18 correlates with that of C_29.

Correlations between units C_14 to C_16 (pebbly silty clays) and section C_2 are less certain, but are most likely to be with units C_24 to C_27, based on their stratigraphic position between the under- and overlying units, whose correlations are firm.

3.3. Interpretation of sediments

Overall, the sediments described above are interpreted as periglacial solifluction and fluvial to marshy, with some evidence of post-depositional weathering. However, sediments from the middle of sections C_1 and C_2 might also be interpreted as glaciogenic based on their structures and composition.

Brecciation of the chalk (clearest in unit B/A1) is attributed to ice segregation within permafrost and/or seasonally frozen ground. Chalk is highly frost-susceptible and so favours ice-lens

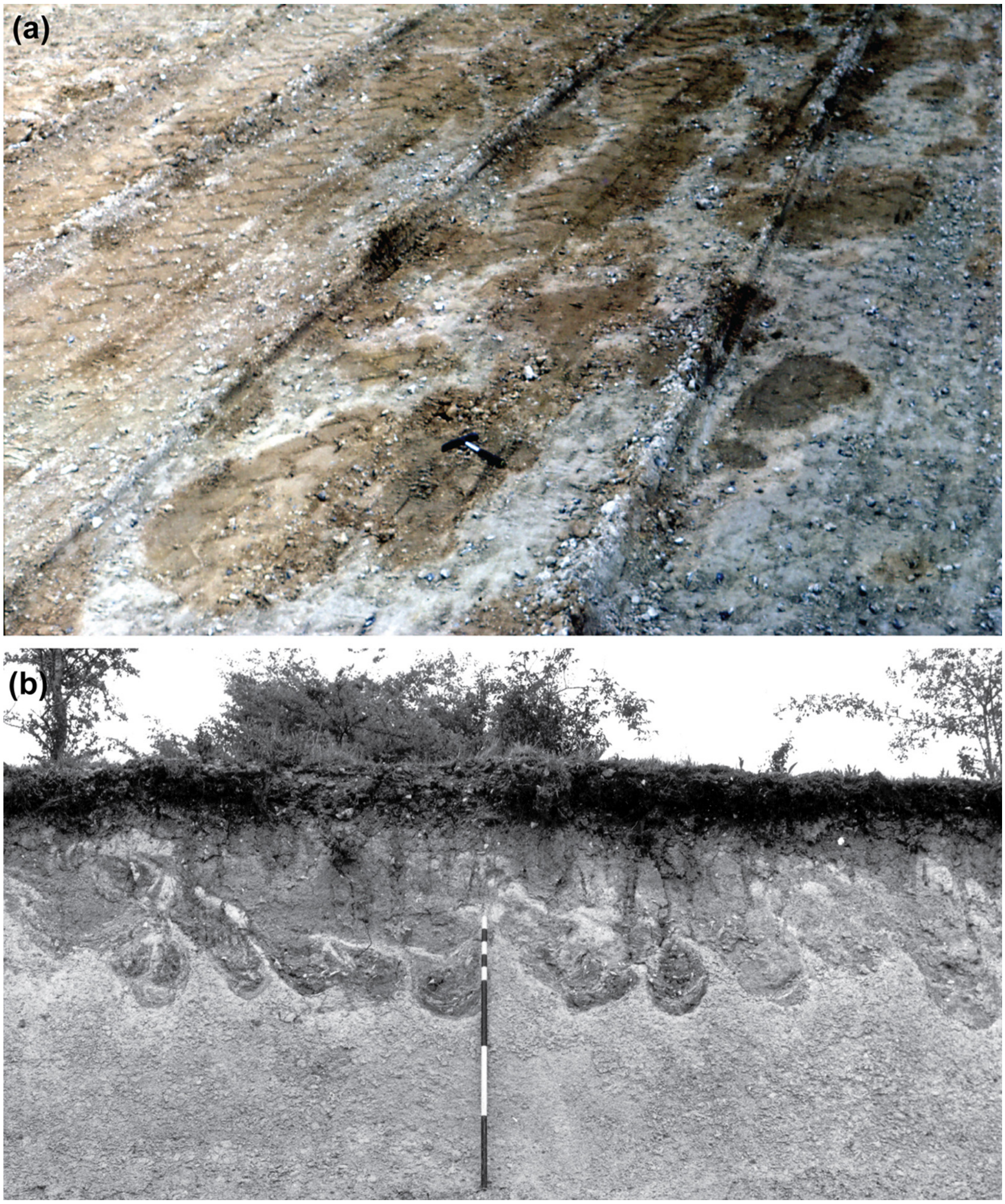

Fig. 7. (a) Horizontal section through involutions in coombe rock and gravel to west of the conveyor belt, in 1971. Hammer for scale. (b) Vertical section through involutions in coombe rock c. 100 m southeast of section A. 1 m pole for scale.

growth and rock fracture. Near-surface brecciation similar to that at Marsworth is widespread in the chalk of eastern and southeastern England (Williams, 1987; Murton, 1996a), and has been reproduced by artificial freezing (Murton et al., 2006).

The chalk diamicton/coombe rock (units $C_1$1, $C_2$1, B/A2 and A2) is attributed to periglacial disturbance of chalk bedrock. Similar chalk diamictons, thought to be predominantly in situ, occur at Birling Gap in East Sussex (Williams, 1971) and Pegwell Bay in Kent (Shephard-Thorn, 1977; Murton et al., 1998). However, the absence of 'matched' sides between adjacent chalk clasts indicates that the clasts have been displaced relative to each other and/or they have been weathered. Such phenomena probably resulted from frost heave and thaw consolidation in the frost-susceptible chalk, although at Marsworth glacial disturbance has also been suggested (Whiteman, 1998).

The silty sandy gravel (units $C_1$2 and $C_2$3) is interpreted as a fluvial lag deposit which overlies the irregular, channelled surface of the chalk bedrock.

The light grey clayey silt of unit $C_1$3 comprises mainly calcareous sediment derived from the underlying chalk, based on the carbonate content, particle-size distribution, fine sand mineralogy and coarse silt mineralogy. Additionally, some mineral components derive from other, unidentified sources. The parting surfaces in the upper part of unit $C_1$3 resemble a platy structure produced by ice segregation (cf. Ballantyne and Harris, 1994, Fig. 6.30b) and brittle fracture (Whiteman, 1998). Molluscan evidence, discussed below, suggests that the clayey silt infilled a stream channel.

Units $C_1$4 and $C_1$6 have undergone pedogenesis and weathering. Pedogenic overprinting has formed a strong prismatic soil structure. Acidic weathering of calcareous sediment similar to that in unit $C_1$3 or $C_1$7 would account for the particle-size distributions but the mineralogy of the fine sand and coarse silt fractions of units $C_1$4 and $C_1$6 is distinct from $C_1$3 and $C_1$7. The mineralogy of these fractions provides incomplete evidence for their provenance, though contributions may have come from the Zig-Zag Chalk and other unidentified sources.

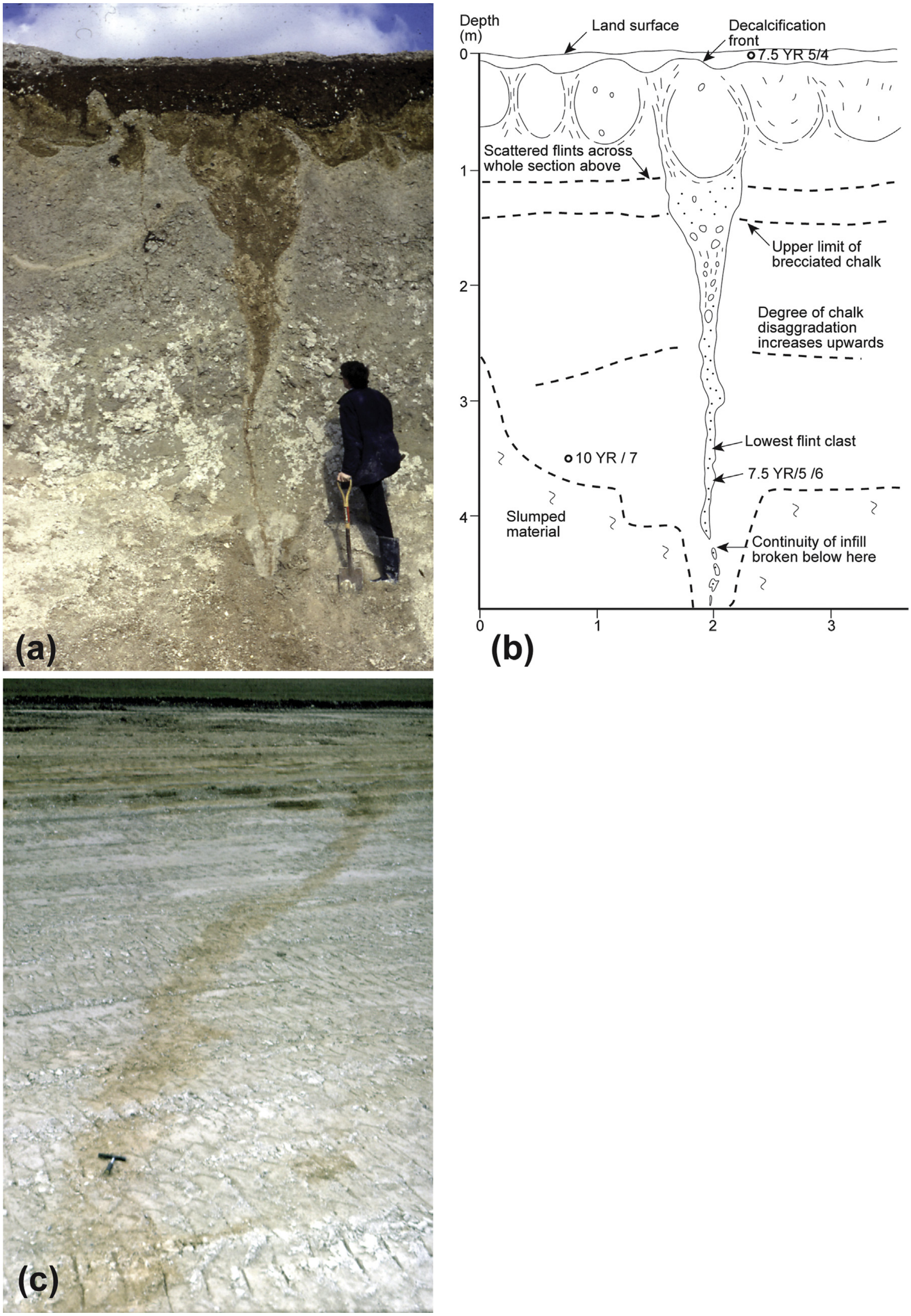

Fig. 8. (a) Photograph of vertical section through ice-wedge pseudomorph penetrating involuted coombe rock and underlying brecciated Zig Zag Chalk, near section A, in 1969. Jim Rose for scale. (b) Sketch of ice-wedge pseudomorph (not at same date as (a)). (c) Photograph of plan view of ice-wedge pseudomorph. Hammer for scale.

Units C_14 to C_16 are difficult to interpret, and may have been emplaced by either periglacial or glacial processes. Subglacial or proglacial deformation could be consistent with the inferred décollement surface within unit C_14 and a range of associated features: the structures around the chalk knoll, the over-folding (with a WSW-ENE strike) and boudinage at the base of C_2, the evidence for brittle fracture in the upper part of C_13, the apparent mobilisation and mixing of C_13 to form the lower part of C_14 and the cross-cutting relation of C_15 (Whiteman, 1998). But shear surfaces, low-angle thrusts and folds also occur in clayey periglacial slope deposits, especially those subject to two-sided freezing of an active layer (e.g. Harris and Lewkowicz, 1993; Ballantyne and Harris, 1994; Murton, 1996b, Fig. 10). The lower part of unit C_14, which grades down into unit C_13 between the 8 and 17 m marks (Fig. 4a; Table 1), can equally be interpreted as either a periglacial slope deposit or a glacitectonite, both locally derived from units C_13 and C_11. Unit C_15 may record: (1) reworking of units C_13 and C_14 by downslope movement and formation of a pebbly lag deposit, similar to the pebbly layer locally found at the base of C_17 (see below), or (2) glaciotectonic emplacement of local material. Unit C_15 contains material derived from unit C_13 and the lower part of unit C_14. Clayey intraclasts within unit C_15 are similar in texture and colour to unit C_13.

The white clayey silt of units C_17 and C_28 is dominated by material derived from the Zig Zag Chalk, but also includes some loessic material indicated by a larger proportion of coarse silt than the chalk. Reworking of pre-existing material is also suggested by incorporation of flint pebbles in the basal lag at the 25 m mark (Fig. 4a), which resemble those in the underlying unit. Reworking by running water (possibly snow meltwater) is inferred from the channel-like, basal angular unconformity (e.g. 23.5–35.0 m and 39–41.5 m marks) and small pebble stringers (e.g. 99 m mark, Fig. 4b). In addition, wind may have deflated chalk surfaces or chalky deposits. The undisturbed strata in the underlying unit C_26, which have erosive bases, are attributed to sheetwash (Table 6), which is consistent with a periglacial rather than glacial interpretation of the middle units of section C_2.

The sand and gravel of units C_18 and C_29 is dominated by locally derived material. The fine sand mineralogy and coarse silt mineralogy suggest that these fractions are dominated by calcareous sediment derived from the Zig Zag Chalk. The cracked flint in the gravel fraction may derive from weathered flint gravel because much of the flint has a brown patina. The sand and gravel is probably of waterlain origin because it overlies a prominent erosion surface (which has subsequently been involuted).

The coombe rock (unit B/A2) and overlying flinty coombe rock (unit B/A3) are attributed to solifluction (Evans, 1966), with many of the chalk clasts derived by downslope movement of fractured chalk. The substantial component of flint pebbles and cobbles in unit B/A3 suggests derivation from the Lewes Nodular Chalk and overlying formations and from the Plateau Drift, probably along the crest of the Chiltern scarp, whereas the absence of flints in the lower subunit of the underlying coombe rock suggests more local derivation, particularly from the Zig Zag Chalk.

The flint gravel (unit B/A4) is tentatively interpreted as a fluvio-periglacial deposit whose flints have been reworked from the underlying flinty coombe rock, prior to its disruption by involution formation.

The overlying pebbly sandy silt (unit B/A5) is probably a slope deposit and may include a loessic component. Finally, the pebbly clayey silt (unit A3) is interpreted as a slope deposit, which contains terrestrial molluscan assemblages, described below, with marsh and temporary-pool elements.

4. Periglacial involutions (Figs. 4–8a and b)

A prominent involuted layer c. 0.5–1.5 m thick extends laterally for at least several hundred metres along most of the conveyor-belt cutting (Fig. 2a). The involutions range in height from several centimetres to at least 1 m, the majority being c. 30–80 cm high.

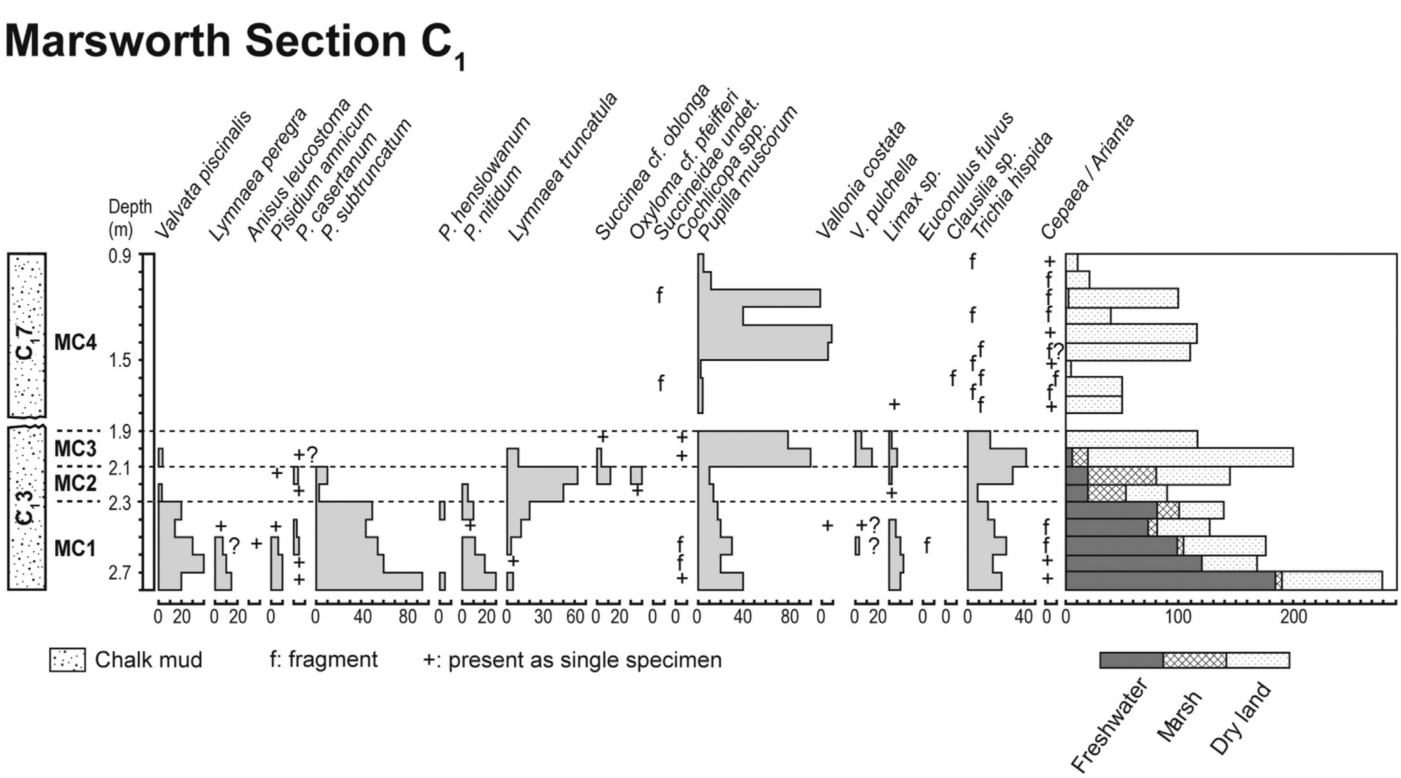

Fig. 9. Mollusc diagram of stratified samples from section C_1. *Limax* sp. refers to *Deroceras/Limax* sp.

They have formed in a wide variety of deposits. In vertical section, they consist of flame structures, diapirs, load casts and ball-and-pillow structures (Figs. 7b and 8a), and in plan view, they range from circular to elongate (Fig. 7a). The margins of involutions vary from sharp and texturally distinct to gradational. Some involutions of sand and gravel at section C_1 have detached from unit C_18 and are completely enclosed in the underlying sediments (Fig. 4a; e.g.–2 to 0 m; and 12–14 m marks).

The involuted layer contains at least two generations of involutions. At the Upper Channel site (Fig. 2b) the channel deposits truncate the involuted layer (Worsley, 1987), indicating that the involutions pre-date MIS 5e. At section B/A, involutions of pebbly sandy silt truncate, and therefore postdate, underlying involutions of coombe rock and flinty coombe rock (Fig. 6). Finally, between sections A and B/A, involutions appear to be superimposed on the top of an ice-wedge pseudomorph (Fig. 8a and b; Worsley, 1987), indicating that they postdate ice-wedge melting.

The involutions are assigned a periglacial origin because of their association with periglacial deposits such as coombe rock, their generally large size and their occurrence in an extensive involuted horizon. They have many similarities with those in a prominent involuted layer above the chalk on Thanet, East Kent (Murton et al., 2003), and like them may have a composite origin involving soft-sediment deformation, cryoturbation and differential frost heave.

5. Thermal contraction crack structures (Fig. 8)

A number of large ice-wedge pseudomorphs were observed by PW in the late 1960s during stripping of the surficial sediments prior to quarrying. In horizontal section, the wedges formed a large-scale polygonal pattern, part of which is shown in Fig. 8c. Today, the only known remaining large wedge, preserved in vertical section, is between sections A and B/A (Fig. 8a and b). The wedge exceeds 3 m in height and penetrates coombe rock and underlying brecciated chalk. The infill comprises a brown silty sandy diamicton, which includes a few clasts of chalk and flints derived from the overlying flinty coombe rock.

Six smaller wedges, c. 1–2 m high, were observed by JGE in 1970 near site B (Fig. 2b), in a 52 m-long vertical section. The tops of the wedges extended down from three different stratigraphic horizons, in ascending order: (1) fine chalk gravel beneath the flinty coombe rock ($n = 1$); (2) flinty coombe rock truncating ($n = 1$) or surrounding the top of wedges ($n = 1$); and (3) stony coversand above the flinty coombe rock ($n = 3$). Thus three episodes of wedge formation are inferred during deposition of the sedimentary sequence.

These wedges are attributed to secondary infilling of thermal contraction cracks. The infills generally comprise host and/or overlying materials, and the wedge size, morphology and stratigraphic association with periglacial deposits (flinty coombe rock and coversand) is consistent with the former occurrence of thermal contraction cracking. The large ice-wedge pseudomorph (Fig. 8) records the occurrence of permafrost probably during MIS 6, because involutions stratigraphically equivalent to those which extend across the wedge infill are also truncated by the Upper Channel deposits (Worsley, 1987).

6. Mollusca

In 1970 nineteen stratified samples for molluscan analysis were collected from section C_1 of the present study; eighteen yielded molluscs. Nine samples weighing c. 1 kg air-dried can be referred to unit C_13 of the present study and one to unit C_14 (Fig. 4a) on the basis of detailed drawings of the stratigraphy initially recorded in 1970 (unpublished data) and re-examined in 1995. The remaining nine samples, each c. 0.5 kg air-dried, can be referred to unit C_17. Samples were processed by washing through 500 μm sieves and sorting under a low-power binocular microscope. Nomenclature follows Kerney (1999).

6.1. The fauna: section C_1 (Table 9; Fig. 9)

The fauna consists of twenty-one taxa, of which only six are common. Eight taxa live in fresh water, three are from marsh environments, and the remainder from land habitats. The most numerous freshwater mollusc is the bivalve *Pisidium subtruncatum* Malm. It is accompanied by other species of *Pisidium* [*P. amnicum*, *P. casertanum*, *P. henslowanum* and *P. nitidum*], of which only the last is common. The most numerous aquatic gastropod is *Valvata piscinalis*.

The marsh element of the fauna is composed largely of the amphibious *Lymnaea truncatula*, but this taxon is accompanied by small numbers of Succineidae tentatively identified as *Succinea oblonga* Draparnaud and *Oxyloma pfeifferi*. The land fauna is dominated by *Pupilla muscorum*, although in unit C_13 *Trichia hispida*, *Vallonia pulchella* and the plates of limacid slugs are also well represented. Abundant throughout the succession are grains of calcite referred to in the 1960s and 70s as the granules of arionid slugs. Reappraisal of these granules (Meijer, 1985; Canti, 1998) indicates that they are produced by the calciferous glands of earthworms.

Spot samples collected during the 1980s and 90s from sediment forming or equivalent to units C_13/C_22 (C/2/91, P23, P21) and C_17 (P24, 2/99) yielded assemblages (Table 9) broadly similar to those recovered from the stratified samples (Fig. 9) though with small numbers of a few additional species.

6.2. Environment indicated by the fauna

The fauna can be divided into four biozones, three (MC1–3) from the lower part of the sequence (unit C_13) and MC4 from the upper part (unit C_17) (Fig. 9).

The fauna from unit C_13 has seventeen species. At the base in biozone MC1, the largest numbers of shells, comprising eight species, are from aquatic environments and suggest deposition in a small water body. Although these taxa could inhabit either a pond or the flowing water of a small stream, it is likely that this assemblage was deposited by the latter, because *V. piscinalis*, *P. amnicum*, *P. henslowanum* and *P. subtruncatum* all strongly suggest moving water. This is also indicated by the numbers of shells of land taxa such as *P. muscorum* and *T. hispida* present in the fauna. Such land shells are rare in true pond faunas because there is no ready mechanism to incorporate them into standing water (Keen et al., 1988). However, they can be introduced into streams by sweeping adjacent land surfaces in times of flood (Sparks, 1961). The numbers of *P. muscorum* alone in MC1 suggest this means of recruitment.

Upwards in biozone MC1, the aquatic species decrease in number, and taxa such as *L. truncatula* increase, suggesting a decline in water flow and replacement by marsh conditions. At 2.3 m most aquatic taxa disappear and the fauna becomes dominated by *L. truncatula*, which is joined at 2.15 m by other marsh species (*S. oblonga* and *O. pfeifferi*) and by increasing values for *T. hispida*. These changes allow the designation of biozone MC2, from 2.3 to 2.1 m. The numbers of wetland snails and the occurrence of *T. hispida* (an inhabitant of disturbed soil and patchy vegetation) suggest that the channel was infilled and replaced by marsh and areas of open, lightly vegetated mud. Such conditions would also be appropriate for the limacid slugs, which continue their same level of representation from MC1.

Above 2.1 m aquatic Mollusca are virtually absent, the marsh taxa are greatly reduced, and the fauna is dominated by large

Table 9
Mollusca from spot samples in section C_1 (except those in Fig. 9) and locations P_{18}, P_{19}, 5/85, P_{10} and P_{11}, and stratified samples from section A.

Site	Section C1					1985/1986 extension of quarry face							Section A (depth in cm)			
Sample number	C/2/91	P23	P21	P24	2/99	P18	P19	5/85	P10a	P10b	P10c	P11	0–15	15–30	30–45	45–60
Valvata piscinalis (Müller, 1774)	139	15	1	–	–	–	8	1	3	2	–	–	–	–	–	–
Bithynia tentaculata (Linné, 1758)	–	–	1	–	–	–	–	–	–	–	–	–	–	–	–	–
Opercula	–	–	–	–	–	1	–	–	–	–	–	–	–	–	–	–
Lymnaea truncatula (Müller, 1774)	23	81	–	–	–	127	3	11	–	–	–	4	23	42	36	24
Lymnaea peregra (Müller, 1774)	3	4	–	–	–	–	–	–	–	–	–	–	–	–	?1	–
Lymnaea sp.	9	7	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Anisus leucostoma (Millet, 1813)	1	1	1	–	–	24	–	–	–	–	–	–	2	1	4	1
Oxyloma pfeifferi (Rossmässler, 1835)	11	19	–	–	–	71	4	20	–	–	–	–	6	10	4	9
Succineidae undet.	3	22	4	–	–	1	4	–	20	5	3	141	–	–	–	–
Azeca goodalli (Férussac, 1821)	–	–	–	2	–	1	–	10	–	–	–	–	–	–	–	–
Cochlicopa lubrica (Müller, 1774)	3	1	1	–	–	–	–	–	–	–	–	–	–	2	2	1
Cochlicopa lubricella (Porro, 1838)	–	–	–	–	–	–	–	–	–	–	–	–	–	cf	cf	–
Cochlicopa sp.		1	5	–	–	–	–	–	–	–	–	–	13	11	9	5
Columella columella (Martens, 1830)	–	–	–	–	–	–	–	–	36	10	–	153	–	–	–	–
Vertigo pygmaea (Draparnaud, 1801)	–	–	–	–	–	1	–	–	–	–	–	–	–	–	–	–
Vertigo antivertigo (Draparnaud, 1801)	–	–	–	–	–	1	1	–	–	–	–	–	–	–	–	–
Vertigo sp.	–	–	1	–	–	2	–	–	–	–	–	–	–	–	–	–
Pupilla muscorum (Linné, 1758)	136	30	46	144	944	321	40	54	486	177	–	101	44	46	51	40
Vallonia costata (Müller, 1774)	–	–	–	–	–	–	–	–	1	–	–	–	?1	1	1	?1
Vallonia excentrica Sterki, 1892	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1	–
Vallonia pulchella (Müller, 1774)	3	2	6	–	–	5	1	–	–	–	–	–	17[b]	15[b]	18[b]	10 [b]
Vallonia sp.	–	2	3	–	–	5	1	3	–	–	–	–	–	–	–	–
Acanthinula aculeata (Müller, 1774)	–	–	–	–	–	1	–	–	–	–	–	–	–	–	–	–
Discus sp.	–	–	–	–	–	1	–	–	–	–	–	–	–	–	–	–
Arion granules[a]	–	–	–	–	–	–	–	–	–	–	–	–	+	+	+	+
Limax sp.	34	1	12	4	2	1	–	54	8	2	1	20	24	20	29	25
Euconulus fulvus (Müller, 1774)	–	–	–	–	–	–	–	–	–	–	–	–	+	1	1	–
Clausilia sp.	–	–	–	2	–	3	1	1	–	–	–	–	–	–	–	–
Helicella itala (Linné, 1758)	–	5	1	–	–	–	–	–	–	–	–	–	–	–	–	–
Trichia hispida (Linné, 1758)	251	100	60	2	1	556	413	354	–	–	–	–	217	319	219	208
Arianta arbustorum (Linné, 1758)	–	–	–	–	–	–	–	–	–	–	–	–	2	2	1	3
Cepaea/Arianta	1	–	3	2	–	1	2	4	–	–	–	–	–	–	+	–
Sphaerium corneum (Linné, 1758)	1	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Pisidium casertanum (Poli, 1791)	10	2	–	–	–	22	3	6	–	–	–	–	–	1	2	1
Pisidium obtusale (Lamarck, 1818)	–	–	–	–	–	–	–	–	–	–	–	–	?1	–	–	–
Pisidium subtruncatum Malm, 1855	6	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Pisidium henslowanum (Sheppard, 1823)	7	–	–	–	–	1	–	–	2	–	–	–	–	–	–	–
Pisidium nitidum Jenyns, 1832	6	–	–	–	–	2	–	–	–	–	–	–	–	–	–	–
Pisidium moitessierianum Paladilhe, 1866	–	–	–	–	–	–	–	–	1	–	–	–	–	–	–	–
Pisidium sp.	51	1	–	–	–	–	–	–	–	–	–	–	2	8	9	7

[a] Now regarded as granules of the earth worm genus *Lumbricus.*
[b] Recorded as *V. pulchella/V. excentrica.*
cf, identified from fragments; +, present.

numbers of *P. muscorum* and with a small increase in *T. hispida*. This biozone (MC3) marks a further drying of the site with the decline to low values of the marsh element, but conditions were not arid because *V. pulchella*, an inhabitant of wet grassland and marsh, attains its highest values in MC3, and the levels of limacid slugs, which also require some degree of moisture, are also maintained. The fauna is, however, almost entirely terrestrial.

Between 1.9 and 1.8 m (unit $C_1$4) the sediments are without Mollusca, probably because this unit has been decalcified, but above 1.8 m in unit $C_1$7, small, then increasing molluscan numbers form biozone MC4. This zone is dominated by fresh and largely intact shells of *P. muscorum*. The only other shells present are fragments of *T. hispida* and *Cepaea/Arianta*, which have a near-continuous presence through the zone, and single fragments of *Clausilia bidentata* and a limacid slug plate. The corroded condition of these fragments suggests weathering and reworking from some earlier sediment, leaving only *P. muscorum* as contemporary with the deposits. Such almost monospecific terrestrial faunas usually indicate conditions of some climatic severity such as would occur early in a cold stage (Keen, 1987). The abundance of the xerophile *P. muscorum* suggests very dry conditions during deposition of

Table 10
Ostracoda from unit $C_1$3, Section C_1.

Depth below 0 m datum[a] (m)	2.79–2.71	2.69–2.61	2.59–2.51	2.49–2.41	2.39–2.31	2.29–2.21
Candona neglecta Sars, 1887	5+f	3	1+2j	–	–	1
Candona angulata Müller, 1900	–	–	–	–	2+f	–
Fabaeformiscandona levanderi (Hirschmann, 1912)	–	–	–	–	2+f	–
Candona sp.	–	–	–	f	–	–
Ilyocypris sp.	–	f	–	j	f	–
Prionocypris serrata (Norman, 1862)	1	1	–	3	–	–
Herpetocypris sp.	f	f	–	–	–	–

[a] Sample locations shown at 21.3 m mark on Fig. 4a and correspond to the six stratigraphically lowest molluscan samples in unit $C_1$3. f = fragments; j = juvenile; numbers are individual valves.

Table 11
The Mammalian fauna from section C_1.

Taxon	N.I.S.	M.N.I.
Proboscidea		
Elephantidae undet., elephant	1	1
Perissodactyla		
Equus ferus Boddaert, horse	12	2
Artiodactyla		
Bovidae undet. (*Bos* or *Bison*), large bovid	2	1

N.I.S = number of identified specimens; M.N.I. = minimum number of individuals.

MC4. The molluscan fauna of unit $C_1$7 strongly indicates deposition under semi-arid conditions of loess steppe. Although few faunas have been reported from British loess (Preece, 1990), there are many records of such restricted faunas from the European mainland (Rousseau and Keen, 1989; Keen, 1995).

6.3. Climatic implications of the fauna

The Mollusca from section C_1 suggest the presence at various times of both aquatic and dry land habitats and both cool temperate and cold climatic conditions. The warmest conditions, indicated by the most diverse fauna, occurred in biozone MC1. Although the total number of species in this zone (18) is, according to Holyoak (1982), typical of those found in interstadial conditions, two other contexts could have provided such a fauna. The aquatic assemblage resembles that of Devensian late-glacial age from northern England, where it colonised new environments such as kettleholes (Keen et al., 1988). These species can tolerate the cool conditions at the start of an interglacial, and can also be found in declining conditions at the end of temperate stages, as well as the temporary ameliorations of climate in interstadials. None of these three climatic interpretations can be ruled out.

The decrease in taxa such as *T. hispida*, and increase in *P. muscorum*, indicate greater aridity, perhaps accompanied by colder conditions. This could be part of any cold stage, because land Mollusca do not give a strong biostratigraphic signal (Keen, 1987). Conditions were not of Arctic severity because *T. hispida*, although an inhabitant of the open ground which normally accompanies periglacial conditions (Keen, 1987), has a restricted northern range at present, only just reaching north of the Arctic Circle in Norway in the relatively oceanic conditions of the Norwegian coast (Kerney and Cameron, 1979). In biozone MC4, arid loess steppe conditions prevailed, probably with Arctic conditions, although no true Arctic/alpine Mollusca have been recovered.

6.4. The fauna: sites P_{10} and P_{11} (Table 9)

Sites P_{10} (samples P_{10a}, P_{10b} and P_{10c}) and site P_{11} lie outside the limits of the Lower Channel and stratigraphically above it (Fig. 2b), from a unit correlated with unit B3 at sections B_{1-3} (Fig. 6). In contrast to other samples, the single samples have a restricted fauna of eight taxa, of which only four are numerous (Table 9). The major taxa in the samples from these sites are *P. muscorum*, limacid slugs, Succineidae, most likely either *Catinella arenaria* or *Oxyloma pfeifferi*, and *Columella columella*. The remaining species, *Vallonia costata*, *Valvata piscinalis, Pisidium henslowanum* and *P. moitessierianum*, all occur in sample P_{10a}, and are represented by only six individuals from a total sample count of 556. The last three of these taxa are freshwater species and incompatible with the overwhelmingly terrestrial/marsh nature of the majority of the fauna, and so it is likely that they were derived from the underlying channel sediments. The faunas from P_{10} and P_{11}, although limited in species, have abundant individuals, with P_{10a} yielding 556 shells

Table 12
Dosimetry, D_e and optical age data from site C and the Lower Channel.

Laboratory code	Stratigraphic unit	NaI γ-spectrometry (in situ) K (%)	Th (ppm)	U (ppm)	Mean γ D_r ($Gy\,ka^{-1}$)	Neutron activation analysis K (%)	Th (ppm)	U (ppm)	Mean β D_r ($Gy\,ka^{-1}$)	Mean Cosmic D_r ($Gy\,ka^{-1}$)	Mean Total D_r ($Gy\,ka^{-1}$)	Mean D_e (Gy)	Age (ka)
GL02079	$C_1$8 (upper sand and gravel)[a]	0.39 ± 0.01	2.68 ± 0.12	0.95 ± 0.06	0.33 ± 0.01	0.39 ± 0.02	2.43 ± 0.12	0.70 ± 0.04	0.40 ± 0.03	0.20 ± 0.03	0.92 ± 0.04	139.7 ± 5.6	151 ± 9
GL02078	$C_1$8 (upper sand and gravel)[a]	0.28 ± 0.01	2.42 ± 0.11	0.90 ± 0.05	0.29 ± 0.01	0.37 ± 0.02	2.60 ± 0.13	0.85 ± 0.04	0.41 ± 0.03	0.19 ± 0.02	0.89 ± 0.04	151.3 ± 5.8	171 ± 10
GL02093	$C_2$8 (white clayey silt)[a]	0.44 ± 0.02	3.42 ± 0.14	1.33 ± 0.09	0.42 ± 0.02	0.66 ± 0.03	4.55 ± 0.23	0.92 ± 0.05	0.67 ± 0.05	0.17 ± 0.02	1.26 ± 0.06	250.4 ± 15.3	199 ± 15
GL02092	$C_1$3 (light grey clayey silt)[a]	0.35 ± 0.02	3.01 ± 0.14	1.00 ± 0.09	0.34 ± 0.02	0.80 ± 0.04	5.56 ± 0.28	1.18 ± 0.06	0.78 ± 0.07	0.15 ± 0.02	1.28 ± 0.08	168.8 ± 12.4	132 ± 12
GL01050	Lower Channel	0.15 ± 0.02	1.74 ± 0.18	0.81 ± 0.09	0.21 ± 0.02	0.09 ± 0.00	1.65 ± 0.08	0.51 ± 0.03	0.14 ± 0.02	0.10 ± 0.01	0.45 ± 0.03	100.4 ± 4.6	224 ± 16
GL02094	Lower Channel	0.09 ± 0.01	1.41 ± 0.09	1.59 ± 0.08	0.27 ± 0.01	0.21 ± 0.01	1.84 ± 0.09	1.34 ± 0.07	0.33 ± 0.03	0.09 ± 0.01	0.69 ± 0.03	162.6 ± 10.5	236 ± 19

[a] Samples listed in order of increasing depth.

and P_{11} 419, from samples taken from small lenses of silt in the predominantly chalky gravel.

The taxa in samples P_{10a}, P_{10b}, P_{10c} and P_{11} indicate deposition in a cold climate. Faunas dominated by limacid slugs, Succineidae and *P. muscorum* are typical of periglacial conditions with open landscapes similar to the modern Arctic tundra (Holyoak, 1982; Keen, 1987). Such conditions are supported by the presence in all of these samples of numerous *C. columella*, one of the few species of European land mollusc whose current distribution is almost exclusively Arctic/alpine (Kerney and Cameron, 1979). This species is the only one of the Marsworth fauna which no longer lives in Britain.

6.5. The fauna: sites P_{18}, P_{19} and 5/85 (Table 9)

These samples came from the infill of a channel in the Zig Zag Chalk near the northern limit of quarrying (Fig. 2b). The faunas are broadly similar to the cool temperate ones in the units C_13 and C_22 at site C. This correlation is supported by the presence of *V. piscinalis* and the fact that the channel infill was overlain by loams containing a restricted mollusc fauna similar to those in the upper part of section C_1. It is also possible, however, that this channel represents a deeper downstream continuation of the Lower Channel at site B.

6.6. Section A Mollusca (Table 9)

The Mollusca from unit A3 in section A closely resemble those from section C_1. They were sorted from four 15-cm thick slices of pebbly clayey silt interbedded between two coombe rock units. The fauna consists of 17 species, of which only *Lymnaea truncatula, Pupilla muscorum, Deroceras/Limax* and *Trichia hispida* are at all numerous. These four taxa are also the most numerous in samples from section C_1 and samples P_{18} and P_{19} from the 1985/86 excavations. Thus we suggest that these assemblages are closely similar in age and environment to those of biozone MC2 in section C_1, representing marshy, open, cool-climate conditions.

7. Ostracoda (Table 10)

Ostracoda were recovered from the six stratigraphically lowest molluscan samples in unit C_13 (Figs. 4a and 5). The five lowest ostracod samples correspond with molluscan biozone MC1, and the highest sample corresponds with biozone MC2 (Fig. 9). Seven ostracod taxa were identified.

7.1. Environment indicated by the fauna

It is difficult to draw anything other than the broadest of palaeoenvironmental conclusions from the ostracod assemblage from unit C_13, as it consists largely of a few juvenile valves and/or fragmentary material. Also the preservation of valves is considerably poorer than those previously reported from the Lower Channel deposits (Murton et al., 2001). Most of the taxa recovered from unit C_13 are eurytopic and found in a range of vegetated aquatic habitats such as springs, ponds, streams and lakes (Meisch, 2000). *Candona angulata* and *Fabaeformiscandona levanderi* are known to tolerate slightly brackish conditions, as do some species of *Herpetocypris* (Griffiths, 1995; Meisch, 2000). *Prionocypris serrata* is perhaps the most diagnostic species present, preferring shallow, calcareous, well-vegetated permanently flowing waters (e.g. Coope et al., 1997; Meisch, 2000; Murton et al., 2001). The presence of adult valves of this relatively large and robust species, along with fragments of other, less well-calcified taxa, suggests that (at least above 2.41 m) the deposits probably represent a shallow, vegetated stream environment. The sediments below 2.41 m may also reflect some degree of water movement, though may equally represent pond or ditch-like conditions.

7.2. Biostratigraphic significance

None of the taxa are biostratigraphically diagnostic, all being known from British and European Quaternary deposits of various ages. *Fabaeformiscandona levanderi*, for example, has a British fossil record extending from the late Beestonian (West Runton Freshwater Bed, Norfolk; de Deckker, 1979) through to the Middle Devensian (Ismaili Centre, London; Coope et al., 1997), though there are no known Holocene or modern records from the UK (Meisch, 2000). *Candona angulata* and *C. neglecta* have similarly long Quaternary records (Griffiths, 1995). Perhaps the most interesting species from a biostratigraphical standpoint is *Prionocypris serrata*, which many researchers regard as synonymous with *Prionocypris zenkeri* (Chyzer and Toth, 1858), though see the taxonomic discussions in Griffiths (1995). *P. zenkeri* is well known from older Quaternary deposits in continental Europe (e.g. the Early Pleistocene Megalópolis Basin, southern Greece; Hiltermann and Lüttig, 1969), but is currently known only from deposits of MIS 7 age and younger in Britain, including the Lower Channel at Marsworth (Murton et al., 2001) and Upper Strensham in Worcestershire (de Rouffignac et al., 1995).

8. Mammalian remains from section C_1 (Table 11)

A small number of mammalian remains, comprising three taxa, were recovered from section C_1. An undetermined elephant is represented by a left humerus of a juvenile individual (M002; Fig. 4a), which was found directly above the contact with the Zig Zag Chalk (Fig. 4a). A large bovid (*Bos primigenius* Bojanus or *Bison priscus* Bojanus) is represented by fragments of a germ of an upper

Table 13
Amino acid ratios (D-Aile/L-Ile) of fossil gastropods from Marsworth.

Cardiff Lab #	Stratigraphic Unit	Taxon/species *intracrystalline	D-Aile/L-Ile ratio (no. of analyses)	Correlation $\delta^{18}O$ stage
UKAL-142C	Organic mud, Lower Channel	*Trichia hispida*	0.1 (1)	5e
UKAL-146	C_12–3		0.15 ± 0 (2)	7
UKAL-147	A3, section A		0.09 ± 0.015 (2)	5e
UKAL-149	C_12		0.14 ± 0.002 (2)	7
UKAL-150B	C_12		0.16 (1)	7
UKAL-151B	C_12–3		0.15 (1)	7
UKAL-155	C_12–3		0.16 ± 0.01 (3)	7
UKAL-157	Stony sandy silt, site B	*	0.09 ± 0.01 (2)	5e
UKAL-159	C_12–3	*	0.18 ± 0.002 (2)	7
UKAL-142	Organic mud, Lower Channel	*Succinea* spp.	0.1 (1)	5
UKAL-158	Stony sandy silt, site B		0.09 (1)	5
UKAL-136	C_17	* *Pupilla muscorum*	0.1 ± 0 (4)	5e
UKAL-148	B3, section B1	*Arianta*	0.1 ± 0.025 (2)	5
UKAL-156	B3, section B1		0.09 ± 0.01 (2)	5
UKAL-160	B3, section B1		0.09 ± 0.01 (2)	5

molar and by a femoral head (cf. Bovini) from the base of unit C_14. Horse is the most abundant species in the assemblage, with 12 identified specimens, the majority recovered from unit C_14. These include fragments of scapula, an articulated distal metacarpal and 1st phalanx, a femoral head, heavily-weathered fragments of a long bone (?tibial) diaphysis (cf. *Equus*), fragments of unerupted upper and lower molars, a single well-worn upper cheek tooth, a distal left third metatarsal (M009) and the head of a right femur (M059; Fig. 4a). Remains of *Equus ferus* Boddaert from unit C_13 comprise a second phalanx and a worn upper cheek tooth. Other fragments were too heavily weathered to identify. The presence of articulated remains implies that there has been little post-depositional transportation of these specimens, while evidence of extensive carnivore gnawing on a femoral head of *Equus* suggests that carcasses were exposed for some time prior to burial.

The paucity of remains renders palaeoenvironmental reconstruction problematic. However, the occurrence of horse implies areas of open grassland. Horse is also significant biostratigraphically, since it was apparently absent from the British Isles for an extended period encompassing the Last (Ipswichian) Interglacial (MIS 5e), the later parts of Stage 5 (MIS 5d–a), MIS 4 and MIS 2, returning briefly only during MIS 3 (Currant and Jacobi, 2001).

9. Geochronology

9.1. Optical dating (Table 12)

Thirteen sediment samples were collected either within plastic tubes (5 cm × 10 cm) or as blocks (15 cm × 15 cm × 10 cm). Under filtered orange light, the core of each sample was retrieved and any fine sand-sized (125–180 μm) quartz segregated by means of dry sieving, alkali (H_20_2) and acid (HCl, HF) digestion and density separation. A sufficient mass of quartz sand was obtained from only six samples (Table 12): three from section C_1 (Fig. 4a), one from section C_2 (Fig. 4b) and two from the Lower Channel deposits described by Murton et al. (2001).

Luminescence estimates of sediment burial period are defined by the quotient of mean equivalent dose (D_e) and dose rate (D_r) values. To generate D_e values, the accumulated optical signal (Huntley et al., 1985) of 12 multi-grain quartz aliquots was stimulated, detected and calibrated using a TL-DA-15 Risø set (Markey et al., 1997), implementing a single-aliquot regenerative-dose protocol (Murray and Wintle, 2000). Mean D_e values were calculated using the central age model proposed by Galbraith et al. (1999). D_r attributable to lithogenic γ and β radiation was determined, respectively, through in situ NaI γ spectrometry using an Ortec μNomad and Neutron Activation Analysis (supplied by Becquerel Australia). Through each technique, the concentration of U, Th and K was quantified and converted to D_r values (Adamiec and Aitken, 1998), accommodating the attenuating effects of grain size (Mejdahl, 1979) and moisture content (Zimmerman, 1971). D_r evolved from cosmogenic muons and electrons was estimated on the basis of global position and overburden thickness (Prescott and Hutton, 1994). Optical ages (Table 12) are quoted at 1σ confidence, which accounts for the propagation of systematic and random errors of D_e and D_r.

The accuracy of quartz-based optical chronologies within the late Middle Pleistocene and/or with D_e values similar to those in Table 12 has previously been substantiated through the concordance of optical age estimates with independent chronological

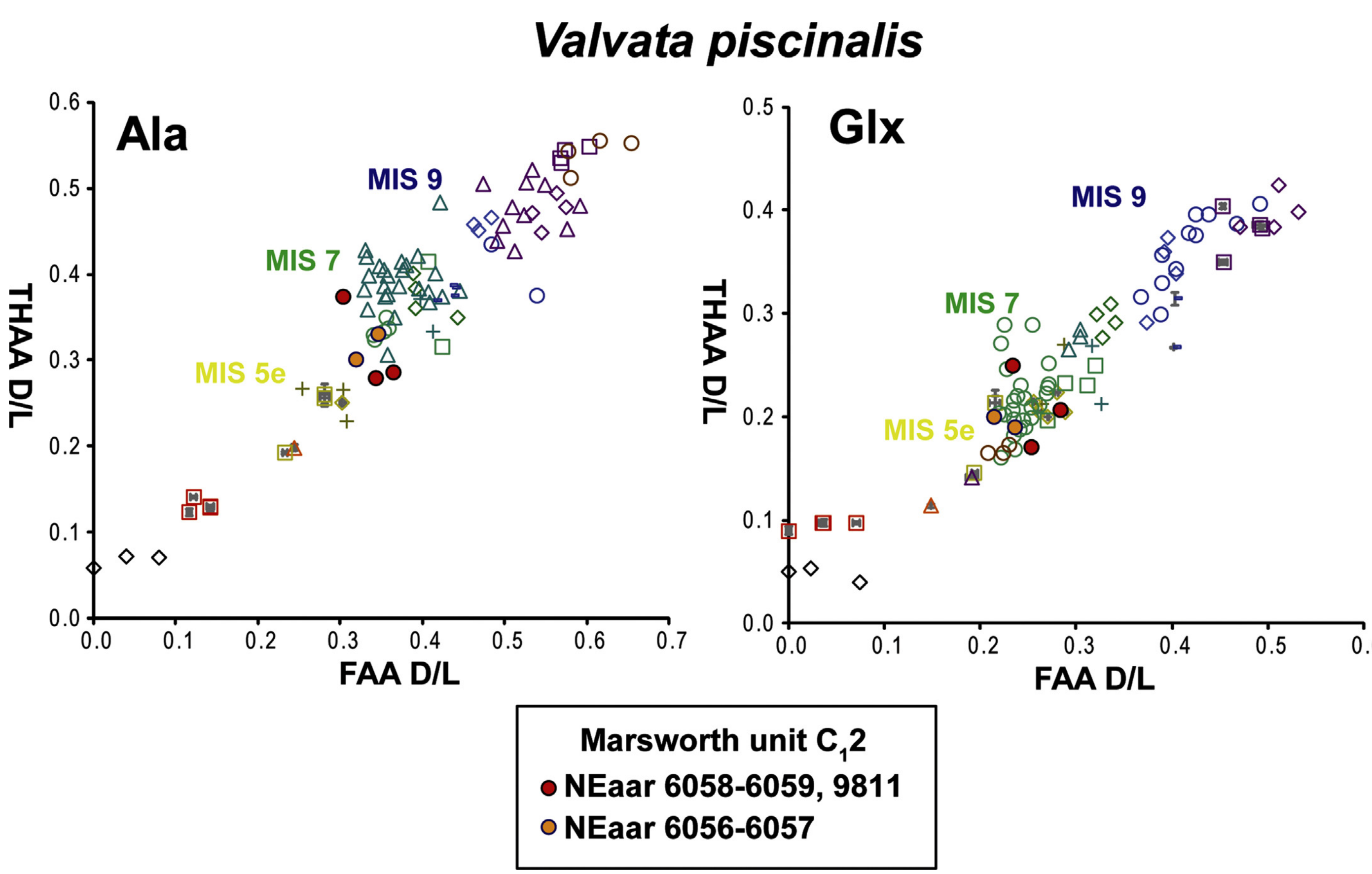

Fig. 10. Free vs Total D/L values of Ala and Glx from bleached *Valvata piscinalis* shells from Marsworth, compared with shells from UK sites correlated with MIS 5e (yellow), MIS 7 (green) and MIS 9 (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

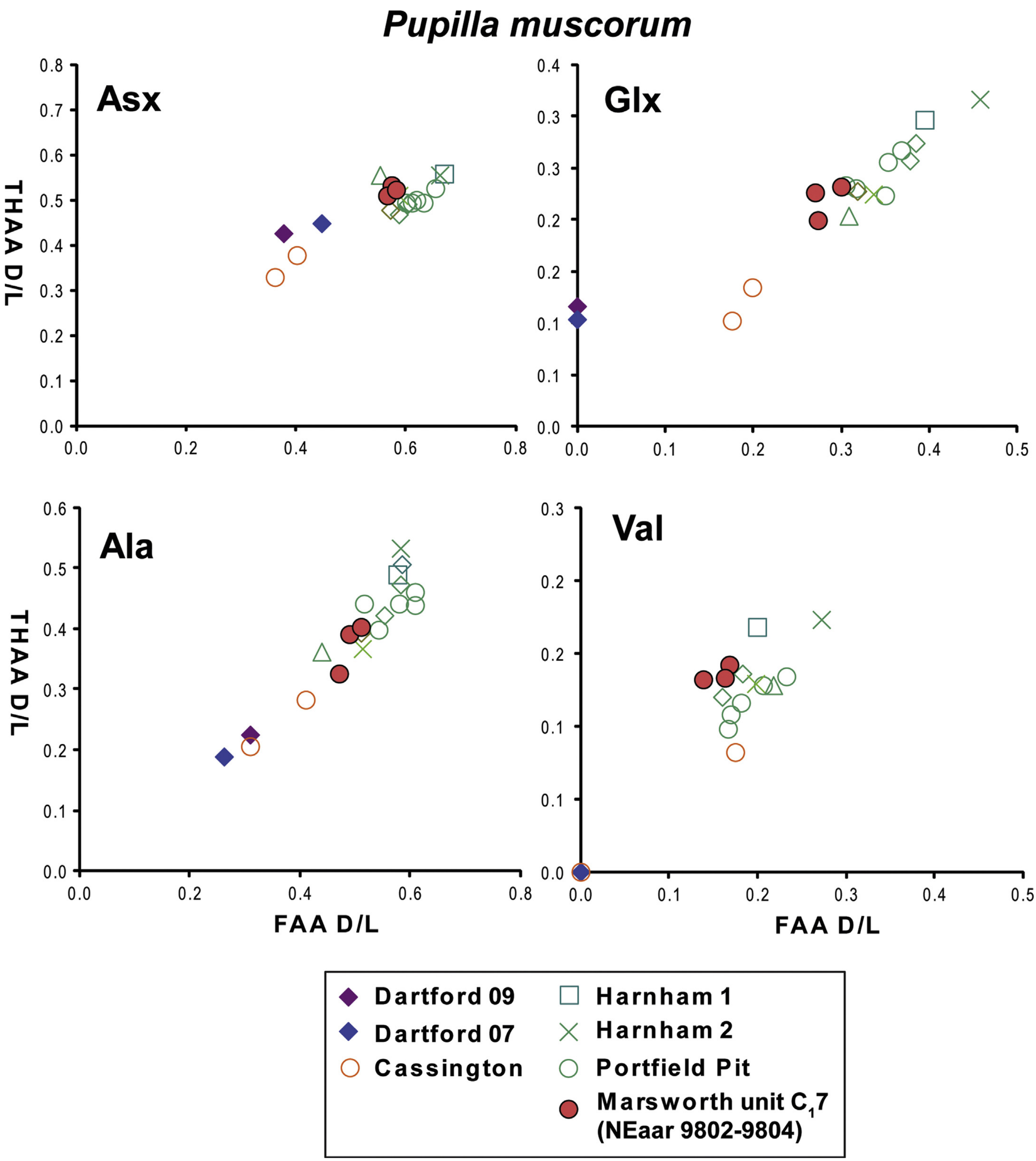

Fig. 11. Free vs Total D/L values of Asx, Glx, Ala and Val from bleached *Pupilla muscorum* shells from Marsworth, compared with shells from other UK sites.

controls (Murray et al., 2002; Murray and Olley, 2002). The MIS 7 age indicated for the Lower Channel deposits by GL01050 (224 ± 16 ka) and GL02094 (236 ± 19 ka) is consistent with that suggested by Murton et al. (2001) on the basis of mammalian and coleopteran biostratigraphy and periglacial stratigraphy, and thus attests to the potential accuracy and utility of optical dating in this age range. An MIS 6 age is inferred for the upper part of sections C_1 and C_2, based on age estimates of 151 ± 9 ka (GL02079) and 171 ± 10 ka (GL02078) from unit $C_1$8 and of 199 ± 15 ka (GL02093) from unit $C_2$8. Dating of the base of section C_1, however, is problematic as an age estimate of 132 ± 12 ka (GL02092) was obtained from unit $C_1$3; the mechanism of this age underestimation remains uncertain.

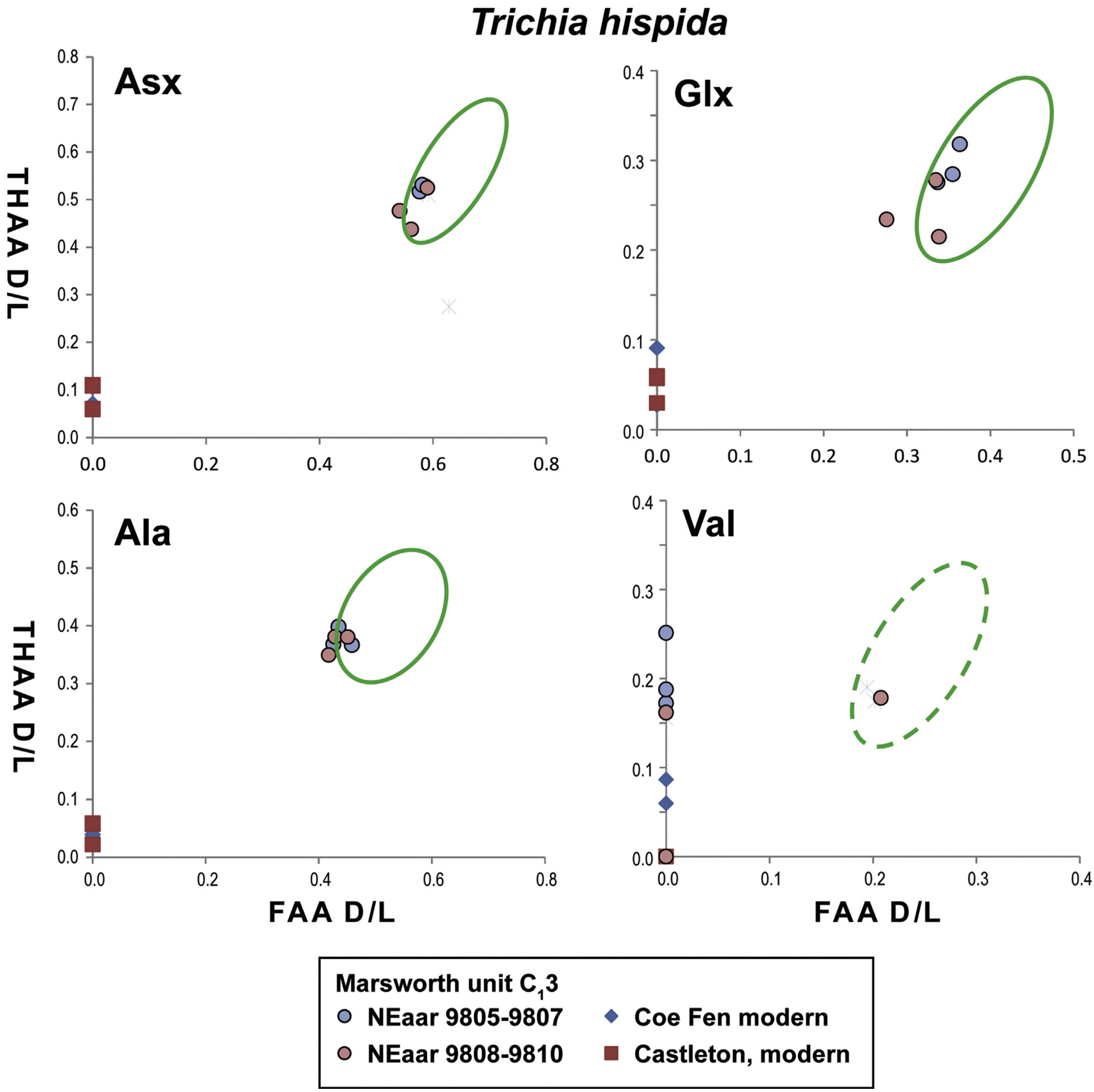

Fig. 12. Free vs Total D/L values of Asx, Glx, Ala and Val from bleached *Trichia hispida* shells from Marsworth, compared with shells from modern material and from UK sites dated by other methods to MIS 6–8, indicated by ellipses as the sites are currently unpublished. The Val ellipse is dashed, as although most of the data fell within this range, this amino acid had particularly high levels of variability. The FAA Val concentrations of some of the Marsworth samples were too low for an accurate Val D/L value to be determined, so are plotted as $x = 0$.

9.2. Aminostratigraphy and amino acid geochronology

Amino-acid analyses of fossil gastropods were carried out independently in two laboratories. The earlier, at Cardiff University, used ion exchange (IEx) high pressure liquid chromatography (HPLC) to determine epimerisation of the protein amino acid isoleucine (L-Ile) to its non-protein diastereoisomer alloisoleucine (D-Aile), expressed as the ratio (D-Ile/L-Ile) on samples collected and analysed between 1995 and 1999; the later, at the University of York, used reverse phase high pressure liquid chromatography phase analysis for the DL ratios of multiple amino acids between 2010 and 2014.

Amino acid racemisation (AAR) is a commonly used tool in Quaternary marine and terrestrial stratigraphy. First used in the USA, analysis was by ion-exchange liquid chromatography using the epimerisation of D-alloisoleucine from L-isoleucine, and later by gas chromatography (GC), which produced DL ratios of many amino acids; but in comparison with D-Aile/L-Ile (which was relatively simple and gave numerical values for stratigraphic units) GC needed larger samples and longer more complicated sample

Table 14
IcPD data from molluscan shells from Marsworth Neaar no.

Neaar no.	Sample name	Asx D/L		Glx D/L		Ser D/L		Ala D/L		Val D/L		[Ser]/[Ala]	
		x	*σ*	*x*	*σ*	*x*	*σ*	*x*	*σ*	*x*	*σ*	*x*	*σ*
6056bF	MarVp1-3.1bF	0.588	0.006	0.215	0.010	0.479	0.321	0.346	0.098	0.200	0.085	0.313	0.011
6056bH*	MarVp1-3.1bF	0.470	0.002	0.200	0.003	0.461	0.225	0.330	0.005	0.184	0.013	0.270	0.069
6057bF	MarVp1-3.2bF	0.613	0.007	0.236	0.018	1.035	0.189	0.319	0.072	0.118	0.166	0.252	0.100
6057bH*	MarVp1-3.2bF	0.456	0.006	0.189	0.007	0.134	0.004	0.301	0.054	0.175	0.032	0.619	0.088
6058bF	MarVp4-6.1bF	0.636	0.000	0.283	0.004	0.887	0.011	0.364	0.018	0.211	0.034	0.277	0.014
6058bH*	MarVp4-6.1bF	0.638	0.007	0.206	0.001	0.707	0.089	0.286	0.013	0.180	0.006	0.225	0.134
6059bF	MarVp4-6.2bF	0.616	0.010	0.234	0.006	0.924	0.035	0.304	0.013	0.257	0.001	0.295	0.061
6059bH*	MarVp4-6.2bF	0.605	0.004	0.250	0.000	0.510	0.033	0.374	0.004	0.264	0.039	0.241	0.145
9802bF	MarPm-1bF	0.575	0.008	0.271	0.006	0.835	0.058	0.490	0.007	0.139	0.005	0.313	0.011
9802bH*	MarPm-1bH*	0.530	0.004	0.225	0.001	0.603	0.008	0.390	0.012	0.132	0.005	0.327	0.002
9803bF	MarPm-2bF	0.568	0.007	0.274	0.000	0.895	0.032	0.471	0.005	0.169	0.021	0.345	0.002
9803bH*	MarPm-2bH*	0.508	0.003	0.199	0.000	0.555	0.007	0.325	0.007	0.142	0.006	0.362	0.001
9804bF	MarPm-3bF	0.582	0.005	0.301	0.005	0.886	0.024	0.513	0.002	0.164		0.290	0.002
9804bH*	MarPm-3bH*	0.521	0.001	0.232	0.003	0.587	0.025	0.402	0.008	0.133	0.005	0.330	0.003
9805bF	MarTh-1bF	0.586	0.002	0.337	0.002	0.909	0.051	0.426	0.006	NR		0.406	0.016
9805bH*	MarTh-1bH*	0.528	0.011	0.275	0.004	0.729	0.046	0.367	0.003	0.172	0.007	0.381	0.004
9806bF	MarTh-2bF	0.577	0.001	0.355	0.029	0.897	0.118	0.435	0.004	NR		0.364	0.014
9806bH*	MarTh-2bH*	0.516	0.006	0.284	0.005	0.733	0.054	0.398	0.001	0.187		0.353	0.008
9807bF	MarTh-3bF	0.581	0.004	0.363	0.023	1.790	0.109	0.459	0.011	NR		0.270	0.013
9807bH*	MarTh-3bH*	0.531	0.001	0.318	0.008	0.682	0.036	0.367	0.009	0.251		0.391	0.039
9808bF	MarTh-4bF	0.541	0.006	0.276	0.013	0.917	0.069	0.429	0.001	0.208		0.404	0.009
9808bH*	MarTh-4bH*	0.476	0.006	0.234	0.003	0.498	0.012	0.381	0.007	0.178	0.012	0.457	0.008
9809bF	MarTh-5bF	0.590	0.001	0.335	0.011	0.874	0.066	0.451	0.000	NR		0.372	0.001
9809bH*	MarTh-5bH*	0.524	0.005	0.278	0.007	0.708	0.028	0.380	0.001	0.161		0.363	0.005
9810bF	MarTh-6bF	0.562	0.003	0.339	0.021	0.884	0.082	0.418	0.004	NR		0.382	0.001
9810bH*	MarTh-6bH*	0.437	0.023	0.215	0.000	0.304	0.002	0.349	0.016	NR		0.595	0.033
9811bF	MarVp4-6.3bF	0.598	0.019	0.253	0.014	0.802	0.101	0.344	0.007	0.000	0.000	0.331	0.017
9811bH*	MarVp4-6.3bF	0.421	0.003	0.171	0.004	0.184	0.022	0.279	0.007	0.000	0.000	0.630	0.069

preparation schemes. The next refinement was reverse-phase high-pressure liquid chromatography (RP-HPLC) (Kaufman & Manley, 1998), which enabled D/L values to be determined for multiple amino acids on mg-size samples. It is the commonest method used today, although D-Aile/L-Ile continues to be used (Wehmiller, 2013). Following the recommendation of Stathoplos and Hare (1993), that NaOCl (sodium hypochlorite – bleach) should be used for sample pre-treatment so as to leave only the intracrystalline amino acids, Gerald Sykes developed this bleaching method in Cardiff for application to Pleistocene shells (Sykes et al., 1995).

In the UK, D-Aile/L-Ile was first used for aquatic bivalves (Miller et al., 1979) and marine gastropods (Andrews et al., 1979; Bowen et al., 1985). DL ratios from terrestrial gastropods, when calibrated by independent means, showed four interglacial events postdating the Anglian glaciation and which were correlated with marine isotope stages 11 (Swanscombe), 9 (Purfleet), 7 (Aveley) and 5e (Trafalgar Square) (Bowen et al., 1989). Significantly, it is compatible with the lithostratigraphy and geomorphology of the Lower Thames valley (Bridgland, 1994; Bowen, 1992, Bowen et al., 1995). Oxygen isotope stages cover many thousands of years, so dependent on which astrogeochronological model is used (Bowen, 2014), this may influence early or late age ascription ($\delta^{18}O$), as in the case of *Pupilla muscorum* (Table 13, UKAL-136).

The application of reverse phase chromatography, using the more diagenetically stable intracrystalline calcite analyses, largely confirmed this 1979 classification (Penkman et al., 2011), but in addition showed that that it was now possible to sub-divide pre-Anglian (stage 12) events of the Cromerian (Penkman et al., 2013).

9.2.1. Cardiff: IEx HPLC D-Aile/L-Ile analyses (Table 13)

Epimerisation of isoleucine is species and temperature dependent but with a sufficient number of species analysed from a lithostratigraphic unit, in a region of similar mean annual temperature, a standardised ratio with a standard deviation (usually below 10%) may characterise that unit for correlation. Such aminostratigraphy (Miller and Mangerud, 1985; Bowen et al., 1985; Bowen and Sykes, 1988; Bates, 1993) when dated by independent means, for example, uranium series dating or luminescence, provides an amino acid geochronology.

At Marsworth, gastropod shells or shell fragments were collected from units $C_1$2–3, $C_1$7 and A3, and their D-alloisoleucine/L-isoleucine (D-Aile/L-Ile) ratios analysed using the methods described in Bowen et al. (1998). Twenty common amino acids are resolved and their chromatograms classified on a scale of 5 (best) to 1 (Bowen, 2000). A careful re-assessment of all samples analysed and deemed reliable is presented on Table 13. Of the 15 samples, 9 are on entire shells and 6 on shell fragments. All samples had a chromatographic quality rating of 3, except for UKAL-159, which was 5. Those below 3 were rejected. Intracrystalline analyses are indicated with an asterisk.

Unit $C_1$7 gave ratios of 0.1 ± 0 (4 analyses) on *Pupilla muscorum*. This species appears to be a slow epimerizer relative to *Trichia* sp., *Succinea* sp. and *Arianta* in samples from central Europe (Oches and McCoy, 1995), although this region would have enjoyed a different palaeotemperature history to that of central England. Thus part of unit $C_1$7 could be mis-correlated with a different MIS (see Section 9.2). Two ratios of 0.09 ± 0.015 were obtained from well-preserved shells of *T. hispida* in Section A, which suggests correlation with sub-stage 5e. Thus it may be inferred that underlying coombe rock is older, and the overlying flinty coombe rock and involutions are Devensian in age.

In a wider context, there are no Mollusca at Marsworth as old as MIS 9. Deposits older than those of MIS 7 age at Marsworth occur some 40 km distant at Hatfield, where D-Aile/L-Ile ratios from *Valvata* of 0.25 are correlated with MIS 9 (Bowen et al., 1989). The Hatfield ratios are similar to those at Trysull, 0.27, from the opercula of *Bithynia tentaculata* (Morgan and West, 1988).

9.2.2. York: RP-HPLC analyses (Table 14, Figs. 10–12)

The current technique of amino acid analysis developed for geochronological purposes (Penkman et al., 2008) combines a RP-HPLC method of analysis (Kaufman and Manley, 1998) with the isolation of an 'intra-crystalline' fraction of amino acids by bleach treatment (Sykes et al., 1995). This combination of techniques results in the analysis of D/L values of multiple amino acids from the chemically protected (closed system) protein within the biomineral, thereby enabling both decreased sample sizes and increased reliability of the result (Penkman et al., 2007, 2011).

Intra-crystalline protein decomposition (IcPD) analyses were undertaken on:

- 3 *Valvata piscinalis* shells, bulked to make two subsamples, from unit $C_1$2 (MarVp1-3.1-2; NEaar 6056–6057);
- 6 *Valvata piscinalis* shells, bulked to make three subsamples, from unit $C_1$2 (MarVp4-6.1-3; NEaar 6058–6059, 9811);
- *Pupilla muscorum* shells, 3 individuals taken to each make three bulked subsamples, from unit $C_1$7 (MarPm1-3; NEaar 9802-9804);
- 3 individual *Trichia hispida* shells from unit $C_1$3 (MarTh1-3; NEaar 9805–9807); and
- 3 individual *Trichia hispida* shells from unit $C_1$2 (MarTh4-6; NEaar 9808–9810).

All samples were prepared using the procedures of Penkman et al. (2008) to isolate the intra-crystalline protein by bleaching. Two subsamples were then taken from each bleached sample; one fraction was directly demineralised and the free amino acids analysed (referred to as the 'free' amino acids, FAA, F), and the second was treated to release the peptide-bound amino acids, thus yielding the 'total' amino acid concentration, referred to as the 'total' hydrolysable amino acid fraction (THAA, H*). Samples were analysed in duplicate by RP-HPLC. During preparative hydrolysis, both asparagine and glutamine undergo rapid irreversible deamidation to aspartic acid and glutamic acid respectively (Hill, 1965). It is therefore not possible to distinguish between the acidic amino acids and their derivatives and they are reported together as Asx and Glx respectively (Figs. 11 and 12).

The DL ratios of aspartic acid/asparagine, glutamic acid/glutamine, serine, alanine and valine (D/L Asx, Glx, Ser, Ala, Val) as well as the [Ser]/[Ala] value are then assessed to provide an overall estimate of intra-crystalline protein decomposition (IcPD). In a closed system, the amino acid ratios of the FAA and the THAA subsamples should be strongly correlated, enabling the recognition of compromised samples (e.g. Preece and Penkman, 2005). The D/L of an amino acid will increase with increasing time, whilst the [Ser]/[Ala] value will decrease. Each amino acid racemises at a different rate, and therefore is useful over different timescales. The D/L of Ser is less useful as a geochronological tool for samples of this age, but is presented here as aberrant values are useful indications of contamination. Whilst developing the research into closed-system protein degradation it became clear that the reaction rates were species-specific, even in the intra-crystalline fraction (Penkman et al., 2007). The pattern of protein degradation with time is different for differing species as AAR is governed by the original protein sequence and conformation. This necessitates the comparison of IcPD data to within a single species, so the data cannot be compared between species. Pilot IcPD aminostratigraphic frameworks have been developed for each of the three species analysed, and although the IcPD for these species has not undergone the detailed study as for some others (e.g. *Bithynia* opercula: Penkman et al., 2013), these datasets allow comparison with samples which have independent age determinations.

- *Valvata piscinalis*: The species analysed from Marsworth with the largest IcPD dataset of material with independent evidence of age is *V. piscinalis* (Penkman et al., 2007). This species has higher levels of natural variability than the calcitic opercula, possibly due to mineral diagenesis of the aragonite to calcite over geological time (Penkman et al., 2010). Despite this variability, it is possible to distinguish Middle Pleistocene material using IcPD, and the samples from Marsworth (Fig. 10) cluster with sites that have been correlated with MIS 7 using other methods (e.g. Stanton Harcourt, Aveley and Latton).
- *Pupilla muscorum*: The database for *P. muscorum* is still being developed and so it is not possible to correlate directly the AAR data to the MIS record at present, but the samples from Marsworth can be compared to material of known age. Although the degradation kinetics of *P. muscorum* are not as well studied as those from other species, the data from the Marsworth samples can be compared to four other sites: Dartford, of Devensian age (Wenban-Smith & Bates, 2011); Cassington, correlated with MIS 5a (Maddy et al., 1998); Portfield Pit, correlated with MIS 6/7 (Bates, 1998); and Harnham, correlated to MIS 8 (Bates et al., 2014). Whilst there is a relatively large degree of spread in the data from these sites, possibly due to the bulking of individual samples required during preparation, the extent of protein degradation in the Marsworth samples would be consistent with a MIS 7 age (Fig. 11).
- *Trichia hispida*: At present there is only a limited IcPD dataset from *T. hispida*, but the Marsworth shells are clearly older than modern material, and fall within the range of data obtained from four other UK sites (Penkman, unpublished data) which are thought to date between MIS 6 and 8 (Fig. 12). This supports the data obtained from the other species of shells from Marsworth.

As highlighted in previous studies, bleaching isolates a fraction of intra-crystalline protein which shows consistent patterns of FAA and THAA racemisation. However, high levels of natural variability within aragonitic shells (compared to that of calcitic biominerals) combined with the low rates of racemisation during cold stages limit the age resolution of these shells. Despite this, the three species of shells from Marsworth do show consistent patterns of degradation with respect to each other, all indicating a likely age for units $C_1$2, $C_1$3 and $C_1$7 that is older than MIS 5e, but younger than MIS 9. The lack of comparative data precludes further resolution.

10. Discussion

The upper part of sections C_1 and C_2 (units $C_1$7–8 and $C_2$8–9) clearly record periglacial conditions during MIS 6, based on the sedimentology (loessic material and gravel), mollusc faunas, OSL dating and amino acid geochronology. We correlate these periglacial units with the sheet of periglacial slope deposits lying stratigraphically between the Lower and Upper Channels (Murton et al., 2001), and with the extensive involuted horizon and the ice-wedge pseudomorphs elsewhere at Marsworth.

The lower and middle parts of sections C_1 and C_2, however, present three problems:

(1) the age and origin of the far-travelled clasts in unit $C_1$2;
(2) the age and palaeoclimatic significance of the mollusc fauna in unit $C_1$3; and
(3) the process(es) that emplaced units $C_1$4 to $C_1$6 and $C_2$4 to $C_2$7.

10.1. Age and origin of the far-travelled clasts in unit $C_1$2, and depositional age of unit $C_1$2

The clast lithological evidence is particularly significant for the glacial stratigraphy at Marsworth. A source for the far-travelled clasts in unit $C_1$2, at the base of section C_1, is difficult to visualise apart from the glacial deposits of Anglian age in the Vale of Aylesbury. This source suggests either that Anglian ice extended some 10 km to the south of the limit inferred by Horton et al.

(1995) and reached the Chalk escarpment near Marsworth or that Anglian glacial sediment was transported south to Marsworth sometime later than MIS 12.

The depositional age of unit $C_1$2 as a whole is uncertain. Significantly, it contains tufa fragments (Table 5). Given that all 13 U/^{230}Th ages previously obtained from Marsworth tufa are within MIS 7 (Candy and Schreve, 2007), we suggest that the simplest interpretation is that unit $C_1$2 was deposited sometime after the fully interglacial conditions of sub-stages 7e and 7c.

10.2. Age and palaeoclimatic significance of the mollusc fauna in unit $C_1$3

The AAR values from both the Cardiff and York studies suggest that the mollusc fauna in unit $C_1$3 is older than MIS 5e and younger than MIS 9. An interstadial age during MIS 6 is considered unlikely in view of the OSL ages of 151 $\pm$ 9, 171 $\pm$ 10 and 199 $\pm$ 15 ka from overlying units $C_1$8 and $C_2$8. Although we cannot discount an interstadial age during MIS 8, we consider that that the fauna most likely dates from MIS 7.

The climate and stratigraphy of MIS 7 are relatively complex (Candy and Schreve, 2007). In high-resolution temperature records such as the EPICA Dome C (Jouzel et al., 2007), the first warm sub-stage (MIS 7e) was significantly warmer (by 3–5 °C) than the later warm stages (MIS 7c and a). This climatic stratigraphy is less clear in other regions of the world, such as sea surface temperature records from the North Atlantic, where MIS 7e, c and a showed comparable levels of warmth (upper part of Fig. 13; McManus et al., 1999; Kandiano and Bauch, 2003). In Britain most deposits attributed to MIS 7 contain evidence for climates comparable to the present day, or possibly a degree or so warmer but still consistent with the Holocene thermal maximum (Candy et al., 2010). No MIS 7 deposits contain evidence for the warmth experienced during those interglacials that, in Britain, appear to have been warmer than the Holocene, i.e. MIS 5, 9 and the Cromerian (Candy et al., 2010). In this respect the environmental proxies preserved in the channels (P_1–P_5 and $C_1$3) at Marsworth are consistent with existing views on MIS 7 climates in Britain.

Schreve (2001) and Candy and Schreve (2007) have demonstrated that the complexity of MIS 7 observed within marine records is also seen in terrestrial deposits of this warm stage. At Aveley, in the lower Thames valley, at least two separate temperate episodes, both attributable to MIS 7, are recorded (Schreve, 2001). The older episode was characterised by (1) climates warmer than the present day (indicated by *Emys orbicularis*), and (2) a woodland ecosystem, identified through the presence of browsing species such as *Palaeoloxodon antiquus*. The younger temperate stage was dominated by grazing species indicative of open grasslands, i.e. *Mammuthus primigenius* and *Equus*. The Aveley deposits are therefore characterised by two mammal assemblage zones (MAZ): the *Pond's Farm MAZ* (recording the older temperate woodland stage) and the *Sandy Lane MAZ* (recording the younger temperate grassland stage) (see upper part of Fig. 13). Other MIS 7 deposits in Britain mainly record the later temperate grassland phase with evidence of temperature regimes that are comparable with, or possibly slightly cooler than, present-day southern England (Coope, 2001; Candy et al., 2010).

At Marsworth, U/^{230}Th dating of tufa fragments suggests that tufa accumulated during MIS 7e and c, and was brecciated and reworked during channel formation in a subsequent temperate episode (Candy and Schreve, 2007). These authors argued that channel formation (P_1–P_7) and infilling at Marsworth, therefore, occurred during MIS 7a. The Lower Channel fill at Marsworth (P_1–P_7) is characterised by remains of vertebrate species diagnostic of open grassland environments, which is consistent with the Sandy Lane MAZ. Furthermore, the coleopteran and pollen assemblages of these channel deposits are also consistent with an open grassland environment with summer temperature regimes similar or slightly cooler than present-day southern England (Murton et al., 2001). Such conditions appear to have been typical of late MIS 7 in Britain and have been ascribed to MIS 7a by Candy and Schreve (2007). The expression of marine isotopic substages in the British terrestrial record is, however, poorly understood (Candy et al., 2014) and it is not impossible that such conditions could also have occurred during late MIS 7c or MIS7b. Support for an age towards the end of MIS 7 comes from the assemblage of mammoth molars from the Lower Channel at Marsworth. After c.200 ka, there is a switch in mammoth molar morphology in Europe, from the steppe mammoth *M. trogontherii* with a mean of 19 plates in the upper M3, to typical forms of woolly mammoth *Mammuthus primigenius* morphology, with a mean of 23 plates in the upper M3 (Lister et al., 2005). However, at Marsworth, Lister and Sher (2001) and Lister et al. (2005) reported a bimodal distribution in the plate counts of the mammoth molars, implying the presence of both *M. trogontherii* and *Mammuthus primigenius* at this time. This suggests that the Lower Channel deposits were laid down at a time when the more archaic indigenous *M. trogontherii* was being replaced by incoming *M. primigenius*. Other MIS 7 sites, such as Ilford (London Borough of Redbridge) and Brundon (Suffolk), contain only *M. trogontherii*, whereas younger assemblages of MIS 6 age, such as those from Balderton (Lincolnshire) and La Cotte de St Brelade (Jersey) contain only *M. primigenius* (Lister and Sher, 2001). The Lower Channel deposits would therefore appear to occupy a chronologically intermediate position, towards the end of MIS 7. Although the possibility of time-stratigraphic mixing cannot be absolutely dismissed, the fact that there is no difference in preservation between the two groups and that they were collected from a sealed context below the organic muds in the Lower Channel both support the above interpretation (Lister et al., 2005). The channel deposits described in the present paper ($C_1$3) are therefore consistent with deposition during the later part of MIS 7, either MIS 7a or late MIS 7b, after the U/^{230}Th dated phases of tufa formation (see lower part of Fig. 13).

The mollusc fauna in units $C_1$2–3 and $C_2$2–3 is thought to be older than that of the Lower Channel deposits at site B, but still within MIS 7. The land snail *Azeca goodalli* is common at site B, but absent in units $C_1$2–3 (Table 9), suggesting that these faunas are not coeval. Additionally, the D-Aile/Ile values of 0.14–0.18 obtained from *Trichia hispida* in units $C_1$2–3 are distinctly greater than the value of 0.1 on the same taxon from the Lower Channel (Table 13), indicating a longer period for racemisation under relatively warm conditions. The preservation of fossil bone at site B is good, with much of the material appearing completely fresh, whereas the bone at site C is uniformly more weathered, consistent with it being of greater age; similarly, the preservation of ostracod valves is noticeably poorer in section C_1 than in the Lower Channel deposits. Lastly, far-travelled clasts in the gravels are substantially more abundant at site C than in the Lower Channel, which is consistent with an earlier date for site C, and with the lower values in the Lower Channel reflecting progressive erosion of the Anglian source material. Based on this evidence we suggest that the fauna in units $C_1$2–3 and $C_2$2–3 dates from MIS 7b or 7a.

10.3. Process(es) responsible for the emplacement of units $C_1$4, $C_1$5 and $C_1$6

Our sedimentological data from units $C_1$4 to $C_1$6 do not discriminate between emplacement of these units by glacial/glaciotectonic processes or reworking by periglacial slope processes. Their fine sand and coarse silt mineralogies are unhelpful in

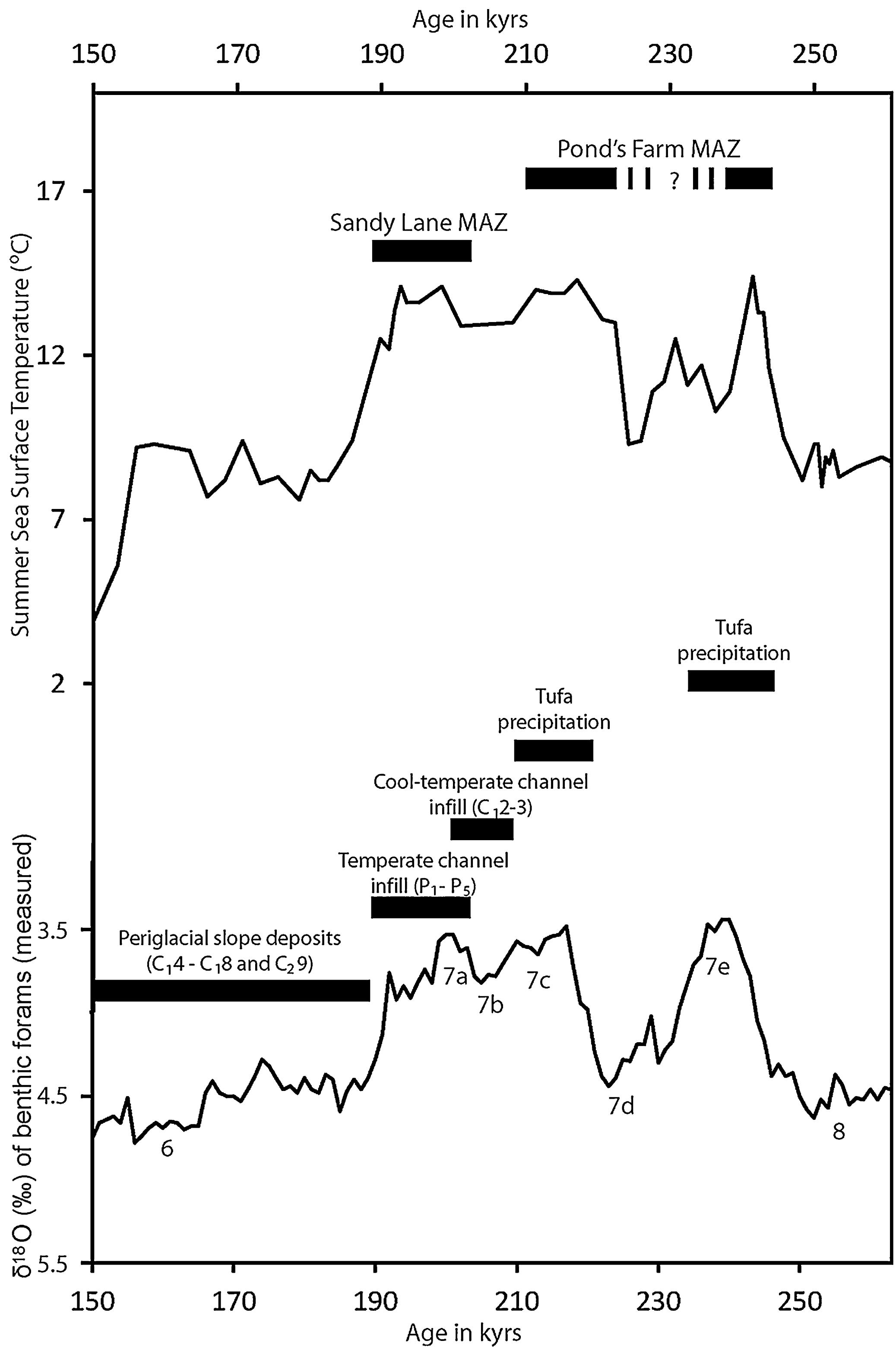

Fig. 13. Suggested relationship between the biostratigraphic assemblages of MIS 7 in the British terrestrial record (top: Pond's Farm MAZ and Sandy Lane MAZ; Schreve, 2001; Candy and Schreve, 2007), geomorphic phases recorded at Marsworth (middle; this study; Murton et al., 2001; Candy and Schreve, 2007) and summer sea surface temperatures from the North Atlantic (M23414 at 53° N, Kandiano and Bauch, 2003) and the LR04 benthic $\delta^{18}O$ stack (Lisiecki and Raymo, 2005).

determining their origin, though it is clear that they incorporate components from sources other than unit $C_1 3$ or the Zig Zag Chalk. Some of this non-local sediment could have been originally transported into the vicinity by glacial processes.

Amino acid dating of unit $C_1 3$ to MIS 7, however, rules out ages of MIS 12 to 9 for the overlying units $C_1 4$ to $C_1 6$. Thus, we reject the hypothesis that units $C_1 4$ to $C_1 6$ were emplaced during the Anglian glaciation. Marsworth is located far beyond the "Wolstonian" MIS 6 glacial limit reported by Gibbard and Clark (2011, Fig. 1), and even supposing MIS 6 glacial ice reached Marsworth we would expect to find reasonably clear and abundant evidence for it (e.g. outwash, widespread till) rather than just the highly weathered

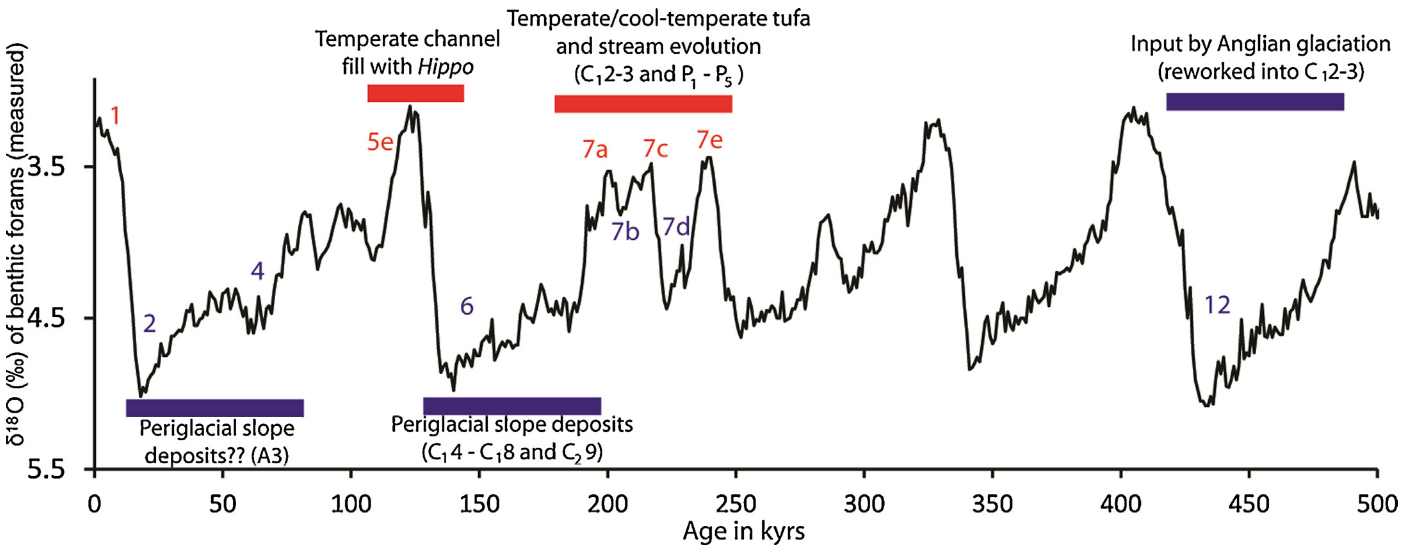

Fig. 14. Suggested relationship between the suggested timing of phases of geomorphological activity as recorded at Marsworth with the LR04 benthic $\delta^{18}O$ stack (Lisiecki and Raymo, 2005).

fragments of pebbly clay at site C. Thus, units C_14 to C_16 were probably emplaced by periglacial processes, reworking pre-existing deposits (potentially including Anglian glacigenic material). These units constitute part of the extensive sheet of periglacial slope deposits that mantles the Icknield Belt platform at the foot of the Chiltern Hills scarp. Distance from the scarp is no problem because weathered remnants of chalky solifluction debris extend up to 10 km north of the South Downs scarp in Sussex (Williams and Robinson, 1983) and cherty solifluction debris extends c. 6 km south of the Hythe Formation scarp near Sevenoaks, Kent (Robinson and Williams, 1984, pp. 17–20).

11. Conclusions

The Middle and Late Pleistocene palaeoenvironmental history reconstructed for Marsworth is illustrated in Fig. 14 and summarised below.

1. The Anglian glaciation probably approached Marsworth but did not actually reach site C. It introduced far-travelled pebbles into the Vale of Aylesbury, some of which are incorporated into the basal sediments (units C_12–3) at section C_1. It is unclear whether the pebbles here were deposited directly from Anglian glacial outwash or were transported some kilometres south of the ice margin by later fluvial activity. The glaciation may also have introduced some sand and silt minerals not derived from local bedrock sources.
2. Variable environmental conditions during the 55 ka-long MIS 7 interglacial at Marsworth are recorded from several different times:

   Fully interglacial conditions during both sub-stages 7e and 7c, when the climate was warm and moist and the area covered in dense woodland vegetation, led to deposition of tufa in springs near the foot of the Chiltern Hills scarp (Candy and Schreve, 2007). Tufa fragments from the Lower Channel deposits at site B preserve a fossil assemblage characteristic of fully interglacial conditions (Murton et al., 2001). Large slabs of this tufa were recorded forming the remains of a slightly disrupted sheet at the base of the site B sequence.

   Cool temperate conditions indicated by molluscan assemblages in units C_12–3 are thought to be older than the Lower Channel deposits, based on higher D-Aile/Ile values from the mollusc *Trichia hispida* and the more weathered condition of bone at the former. Such conditions may have occurred during sub-stage 7b or 7a or possibly 7d. The fauna lived in a small spring-fed stream that infilled with calcareous sediment, leading to marshy conditions.

   Temperate conditions about as warm as those of today in central England occurred towards the end of MIS 7 (probably sub-stage 7a), inferred from the vertebrate remains, pollen, Coleoptera and molluscan remains from the Lower Channel (Murton et al., 2001). The associated stream originated near site B and extended through sections P_{1-5} in a north-westerly direction (Fig. 2b). The elevation of the channel falls from 125.4 m O.D. at P_{13} to 122.8 m near P_6, and its extension towards the southwest is suggested by the distribution of tufa, bone and ivory in the sediments and by channel remnants in sections P_{10}, P_{18} and P_{19}.
3. *Cool temperate conditions* during sub-stage 7a are indicated in the channel infill sampled for Mollusca at P_{18}, P_{19} and 5/85. Subsequent climate cooling during later stages of channel infilling is inferred from Coleoptera and pollen evidence (Murton et al., 2001).
4. Intense periglacial activity characterised MIS 6. Thermal contraction cracking led to growth of ice wedges in permafrost and possibly of small soil wedges in the active layer. Ice segregation in perennially and seasonally frozen ground fractured the upper c. 0.5–3.0 m of the chalk beneath the Icknield Belt platform and the Chiltern scarp, producing abundant chalk clasts. Aeolian activity deposited loess on the Chilterns and adjoining terrain, and windblown sand locally at site B (Murton et al., 2001). Mass movement and slopewash reworked the coarse, frost-shattered chalk, loess and pre-existing sediments, redepositing them downslope as coombe rock, silty and clayey loams and pebble stringers. Fluvial erosion and deposition, probably with a strong snowmelt regime, eroded and reworked some of the pre-existing sediments, depositing non-fossiliferous sand and gravel (units C_18 and C_29). An MIS 6 age is supported by OSL age estimates of 151 ± 9 and 171 ± 10 ka from the upper sand and gravel (unit C_18) and approximately by the OSL date of 199 ± 15 ka from the underlying white clayey silt (unit C_17). Units C_14–6 and their contained deformation structures are thought to represent weathered and periglacially disturbed slope sediments deposited during MIS 6, rather than weathered till of Anglian age.
5. Fully interglacial conditions during MIS 5e are represented by the Ipswichian mammal fauna in the Upper Channel

(Murton et al., 2001). Soil formation and acidic weathering of near-surface sediments during both the MIS 5e and 7 interglacials caused weathering of some near-surface sediments (e.g. units $C_1$4 to $C_1$6 and the upper part of unit $C_1$3).

6. Further dating of sediments from sections A and B/A is required to determine if periglacial slope deposits and involutions of Devensian age are present, as tentatively suggested by a single D-Aile/L-Ile ratio from unit A3.

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